UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

ORGANIC-MATTER CONTENT OF APPALACHIAN DEVONIAN SHALES DETERMINED BY USE OF WIRE-LINE LOGS-SUMMARY OF WORK DONE 1976-80

By

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Contents

Illustrations

Illustrations--Continued

ABSTRACT

The organic-matter content of the Devonian shale of the Appalachian basin is an important characteristic for assessing the natural-gas resources of this shale, and patterns of organic-matter distribution convey information on sedimentary processes and depositional environments. In most of the western part of the Appalachian basin, the organic-matter content of the Devonian shale can be estimated from formation-density wire-line logs (density-log method) using the equation

$$\phi_o = (\rho_B - \rho) / 1.378$$

and from gamma-ray wire-line logs (gamma-ray method) using the equation

$$\phi_o = (\gamma_B - \gamma) / 1.378A$$

where ϕ_o is the organic-matter content of the shale (fractional volume), ρ the formation density (g/cm^3), ρ_B the formation density if no organic matter is present (g/cm^3), γ the gamma-ray intensity (API units), γ_B the gamma-ray intensity if no organic matter is present (API units), and A the slope of the crossplot of gamma-ray intensity and formation density (API units/(g/cm^3)).

In 74 intervals of varying thickness and organic-matter content from 12 widely separated test wells, the distribution of differences between volume-percent organic-matter content measured by laboratory analyses of core samples and that estimated from formation-density logs has a mean of 0.15 percent and a standard deviation of 1.55 percent; the distribution based on gamma-ray logs, excluding the Cleveland Member of the Ohio Shale and the lower part of the Olentangy Shale, has a mean of 0.44 percent and a standard deviation of 1.98 percent. The accuracy of the density-log and gamma-ray methods is adequate for most geologic applications.

Both methods can be used in a region of applicability that includes most of the western part of the Appalachian basin. Outside this area, gamma-ray intensity is not a reliable indicator of organic-matter content, and doubt is also cast on the density-log method because the gamma-ray intensity does not provide independent confirmation of the method's fundamental assumptions. Within the region of applicability, the gamma-ray intensity of the Cleveland Member of the Ohio Shale and the lower part of the Olentangy Shale is anomalously lower than that of other Devonian shales of similar organic-matter richness, so that organic-matter content computed for these two units by the gamma-ray method is likely to be too low.

The distribution of organic matter in the organic-matte&rich facies of the Devonian shale (defined here as shale containing 2.0 percent or more organic matter by volume) is characterized in the western part of the Appalachian basin by use of data derived from density logs. The thickness of organic-matter-rich facies ranges from less than 300 ft (91 m) in east-central Kentucky to 1,000 ft (305 m) along the Kentucky-West Virginia border. The average organic-matter content of the organic-matter-rich facies increases from 5 percent by volume in the central part of the Appalachian basin to 16 percent in east-central Kentucky. The histogram of organic-matter-content values within the organic-matter-rich facies is closely approximated by the exponential curve $y = 1.1e^{-0.288x}$ in New York, Pennsylvania, and West Virginia, but in Ohio, Kentucky, and Virginia, the histogram shifts towards higher values of organic-matter content and is not well represented by an exponential function. The net thickness of the blanket of organic matter contained in the organic-matter-rich facies ranges from about 20 to 80 ft (6.1-24.4 m) within the mapped area, and local depositional maxima are centered in Martin County, Kentucky, eastern Pike County, Ohio, and northern Ashland County, Ohio.

INTRODUCTION

The initial objective of the study described in this report was to utilize the borehole-gravity meter, which has a large radius of investigation, to study fracture porosity in the Devonian shale of the Appalachian basin. Five borehole-gravity surveys were run by the U.S. Geological Survey in West Virginia in 1976 and 1977 (Schmoker, 1976, 1977; Schmoker and Kososki, 1977; Schmoker and others, 1977). Interpretation of the borehole-gravity surveys in terms of formation density led to these conclusions:

1) The effect of fracture porosity in the Devonian shale upon formation density is negligible.

2) Organic-matter content is the primary factor causing changes in formation density in the Devonian shale.

3) Formation densities measured with the conventional gamma-gamma density log are accurate and representative of the Devonian shale section.

These results left little incentive to continue the borehole-gravity work, although the borehole-gravity meter would be a good logging tool to use in the recompletion of existing Devonian shale wells because data are not significantly affected by wellbore conditions and casing.

On the positive side, however, these results suggested a direction for new research. Analyses of core samples from initial Devonian shale wells drilled in the Appalachian basin under contract to the U.S. Department of Energy (DOE) showed that natural-gas resources and organic-matter content of the shales are related. Because too few wells were going to be drilled in the DOE program to map organic-matter content adequately throughout the basin by analysis of cores alone, the emphasis of this project shifted to the study of organic-matter content using formation-density and gamma-ray wire-line logs. This report summarizes the author's investigations of Devonian black shale in the Appalachian basin (Schmoker, 1978, 1979, 1980a, b).

ADVANTAGES OF WIRE-LINE METHODS

The Devonian shales are vertically heterogeneous, and organic-matter content of the shale can vary sharply in vertical distances of a meter or less (Leventhal and Shaw, 1980). Conventional wire-line logs measure formation properties continuously, but laboratory analyses are discrete, and measurements of a few samples may not properly define average formation properties. For example, the volume-percent organic-matter content determined by two laboratories for four intervals of a well cored by DOE in Perry County, Kentucky, differs by 2.2 percent, -1.1 percent, -2.1 percent, and 3.1 percent. In a well cored by DOE in Martin County, Kentucky, average organic-matter content measured by different laboratories differs by as much as 3.7 percent 'in organic-matter-rich intervals and 2.7 percent in organic-matter-poor intervals. Such nonsystematic differences are probably due mainly to limited sampling of heterogeneous strata.

Wire-line logs also have a significant advantage over core analysis in terms of data availability. Logs are now run in virtually all wells drilled for hydrocarbons in the Devonian shale. The gamma-ray Log is probably the most frequently obtained wire-line log in the Devonian shale sequence, and the formation-density log is commonly run also. The cumulative pool of these wire-line logs forms a large and geographically broad data base.

Thus, by substituting the analysis of wire-line logs for the laboratory measurement of core samples, two significant advantages are realized:

1) Wire-Line Logs are more common and more available than core samples.

2) Continuously recorded wire-line logs eliminate the statistical uncertainties of limited sampling of the shale sequence.

Although economic comparisons have not been made, the estimation of organic-matter content from wire-line logs may also be less expensive than the laboratory analysis of core samples.

TMPORTANCE OF ORGANIC-MATTER CONTENT

Organic-Matter Content and Natural-Gas Resources

The Devonian shales are not reservoir rocks in the normal sense of the word. Commercial gas production appears to depend upon permeable pathways such as fractures, and perhaps silty beds, to conduct gas to the wellbore. Recharge of the permeable system in response to the disequilibrium induced by the well is proportional to the volume of movable gas in the matrix. All else being equal, an increase of gas in the matrix will result in higher production rates and larger recoverable reserves.

Laboratory analyses show a general tendency for the volume of movable gas in the shale matrix to increase as organic-matter content increases (E. C. Smith, written commun., 1978; Science Applications, Inc., 1978, p. 54; G. E. Claypool, written commun., 1979). Thus, organic-matter content can be related to gas in place and is an indirect measure of the recharge capacity of the shale.

The significance of organic-matter content in gas production is supported by the common division of the shale into "black" and "gray" facies. The darker zones, which contain more organic matter, are usually more productive than the organic-matter-poor "gray" zones and are often the only intervals considered prospective in the western part of the Appalachian basin (see, for example, Bagnall and Ryan, 1976; Patchen, 1977). The National Petroleum Council (1980, p. 30) found that average initial production rate and thickness of the "black" shale section correlate on a county-by-county basis.

Organic matter is the source of natural gas in the Devonian shale and is thus a measure (when considered along with factors such as chemical composition and thermal maturity) of total gas generated. Organic-matter content can affect mechanical properties basic to the design and effectiveness of well stimulations. 'It is a key factor affecting *in* situ retorting or thermal-recovery processes, and uranium and other trace metals of possible economic or environmental importance are concentrated in organic matter. For these reasons, the development of methods and data for determining the amount and area1 distribution of organic matter in the Appalachian Devonian shale is important and timely.

Organic-Matter-Rich and Organic-Matter-Poor Facies

The Devonian shale section is often divided into organic-matter-rich ("black") and organic-matter-poor ("gray") units. Some coarser grained "gray" shale may produce gas, but the organic-matter-rich shale facies are believed to contain the bulk of the producible gas resource. Therefore, Devonian shale studies usually emphasize the organic-matter-rich facies, but the definition of such facies is not standardized.

Traditionally, the color of the shale has been the criterion for separating the shale sequence into organic-matter-rich and organic-matter-poor facies. The basic validity of this approach is established by the data of Hosterman and Whitlow (1980) which show a strong correlation between color value and organic-matter content for organic-matter content up to about 10 percent by volume (fig. 1). The problem is that "black" is a subjective classification, and the method's internal consistency and relation to other studies are difficult to establish. Probably the facies boundary picked by geologists would typically be represented by dry pressed-powder cuttings having a color value corresponding to about 4 percent organic matter by volume.

Other definitions of the boundary between organic-matter-rich and organic-matter-poor facies are based on gamma-ray logs, wlth the assumption that natural gamma radiation and organic-matter content correlate. Defining

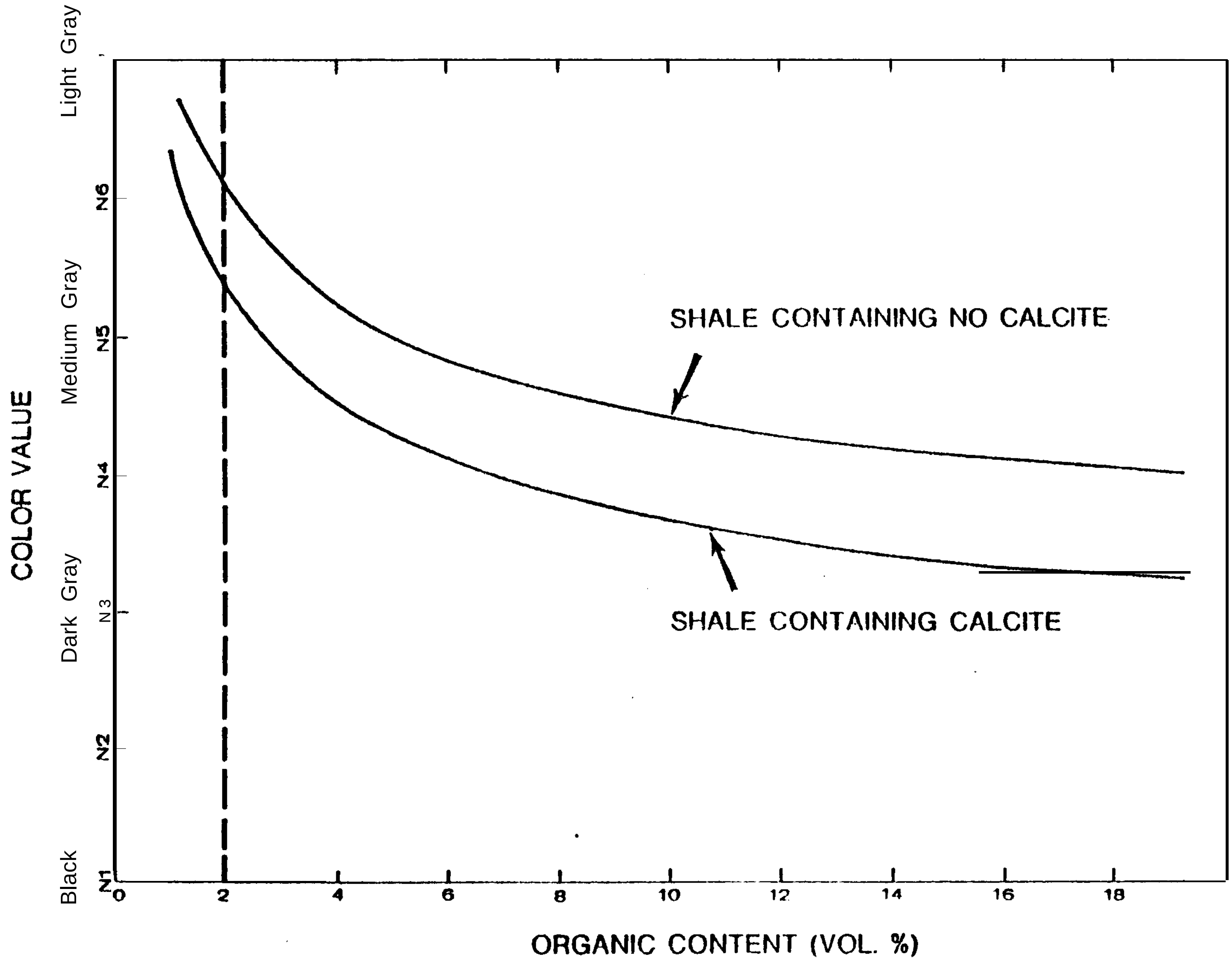

Figure 1.--Relation between Devonian shale color based on the Munsell system (Goddard and others, 1948) and volume-percent organic-matter content (adapted from Hosterman and Whitlow, 1980).

organic-matter-rich facies on the basis of gamma-ray methods is less subjective than defining these facies on the basis of color. Results should be consistent if the gamma-ray logs are corrected to uniform wellbore conditions. However, gamma-ray methods are adversely affected by three regional characteristics of the Devonian shale:

1) The shale baseline - the gamma-ray intensity if no organic matter is present - varies regionally throughout the basin.
2) The change in gamma-ray intensity per unit change in organic-matter content varies regionally throughout the basin.
3) In the eastern part of the basin and in central Kentucky, gamma-ray intensity and organic-matter content do not correlate.

A gamma-ray intensity of 20 API units above the gray-shale baseline (20-API method) is one definition of the boundary between organic-matter-rich and organic-matter-poor facies (e.g., see Piotrowski and others, 1978, p. 129). The organic-matter content of Devonian shale having a gamma-ray intensity 20 API units above the baseline is plotted in figure 2. This figure, which shows the minimum organic-matter content of organic-matter-rich facies defined by the 20-API method, is based on wire-line data from the well locations shown in figure 3.

The average organic-matter content of shale at the organic-matter-rich boundary defined by the 20-API method is about 1.8 percent by volume, but it varies along a regional trend roughly paralleling the basin axis from a low of about 1.0 percent in Kentucky to a high of 2.6 percent in western Pennsylvania. Within the area shown in figures 2 and 3, the 20-API method places more shale in the organic-matter-rich facies than does the separation based on shale color.

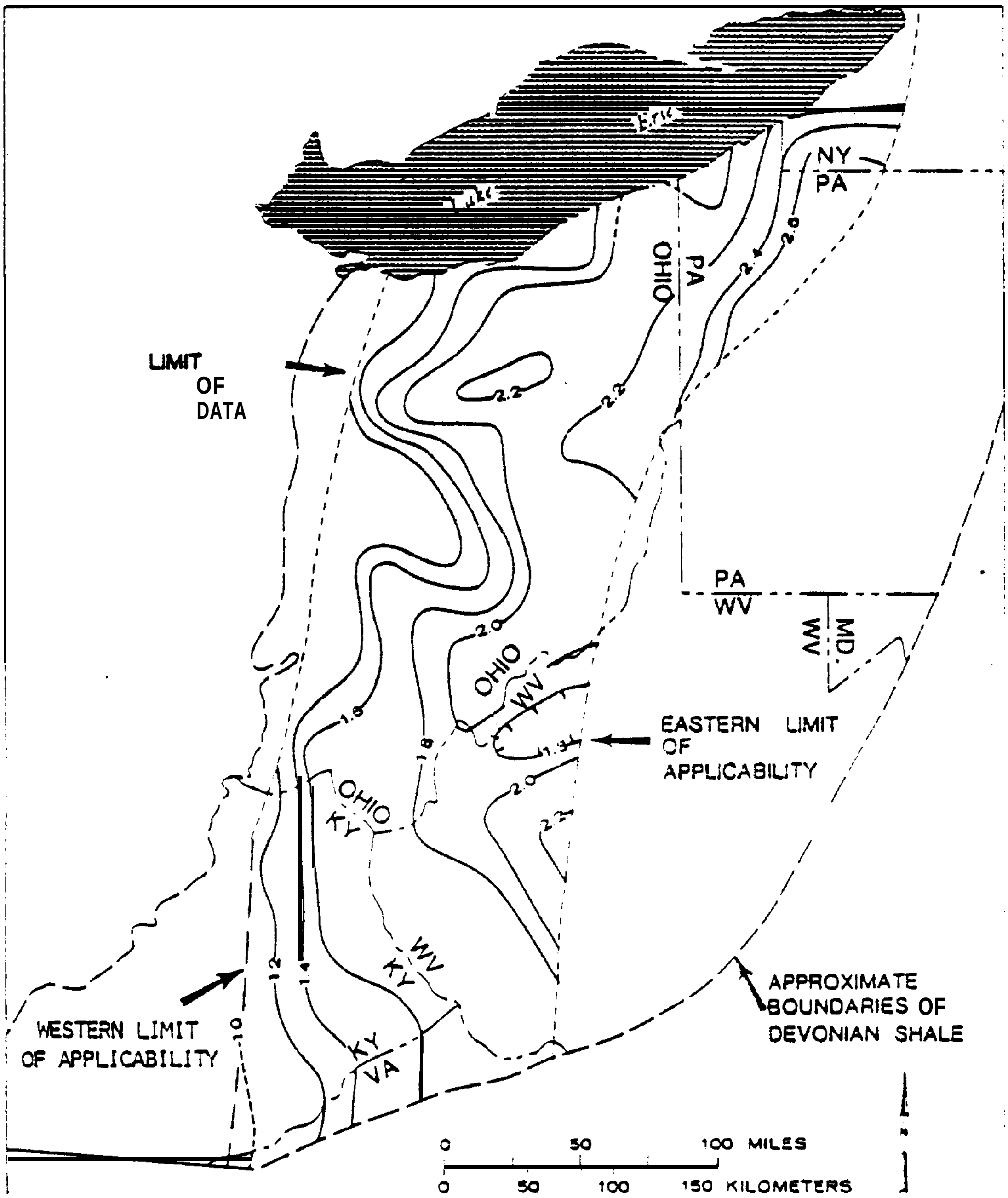

Figure Z.--Organic-matter content (volume percent) of shale having a gamma-ray intensity 20 API units above the shale baseline. An air-filled wellbore and a baseline corresponding to shale containing no organic matter are assumed. Contour interval = 3.2 percent.

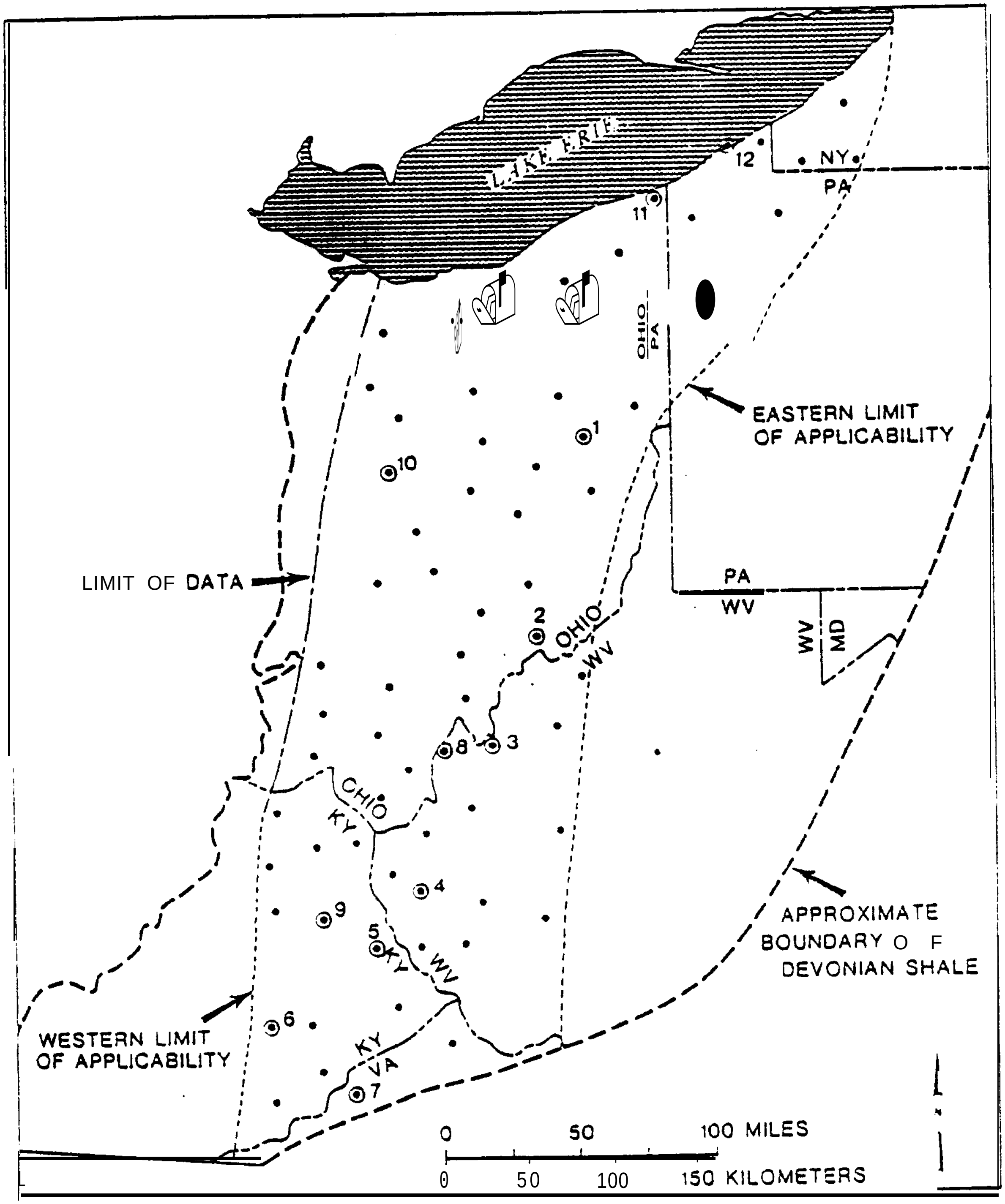

Figure 3.--Locations of wells within the region of applicability where wire-line data were obtained. 'Jells for which organic-matter content computed from wire-line logs is compared to laboratory analyses are circled and numbered by county : (1) Carroll, OK; (2) Washington, OH; (3) Jackson, WV; (4) Lincoln, WV; (5) Martin, KY; (6) Perry, KY; (7) Wise, VA; (8) Mason, WV; (9) Johnson, KY; (10) Knox, OK; (11) hshtabula, OH; (12) Erie, PA.

A gamma-ray intensity of 230 API units has been used as the threshold value for shale of high gas content (National Petroleum Council, 1980) and could thus be regarded as another definition of the boundary between organic-matter-rich and organic-matter-poor shales (230-API method). The organic-matter content of Devonian shale having a gamma-ray intensity of 230 API units is plotted in figure 4. This figure shows the minimum organic-matter content of organic-matter-rich facies defined by the 230-API method.

The average organic-matter content of shale at the organic-matter-rich boundary defined by the 230-API method is about 6 percent by volume, but it varies locally from 4 to 10 percent. Within the area shown in figure 4, the 230-API method probably places less shale in the organic-matter-rich facies than does the separation based on shale color, and places significantly less shale in the organic-matter-rich facies than does the 20-API method.

Gamma-ray methods for defining organic-matter-rich facies depend upon a covariance between gamma-ray intensity and organic-matter content. This covariance weakens or disappears beyond the limits of applicability shown in figures 2, 3, and 4. Outside these limits (which are discussed under REGION OF APPLICABILITY), gamma-ray methods for defining organic-matter-rich facies are unreliable.

The boundary between organic-matter-rich and organic-matter-poor facies favored here is defined as an organic-matter content of 2 percent by volume. This definition is quantitative, regionally invariant, and applicable to the entire basin. It is an improvement over the definitions discussed above, provided sufficient data on organic-matter content can be obtained from laboratory measurements or from wire-line logs.

The boundary value of 2 percent organic-matter content by volume is somewhat arbitrary but is chosen for two reasons:

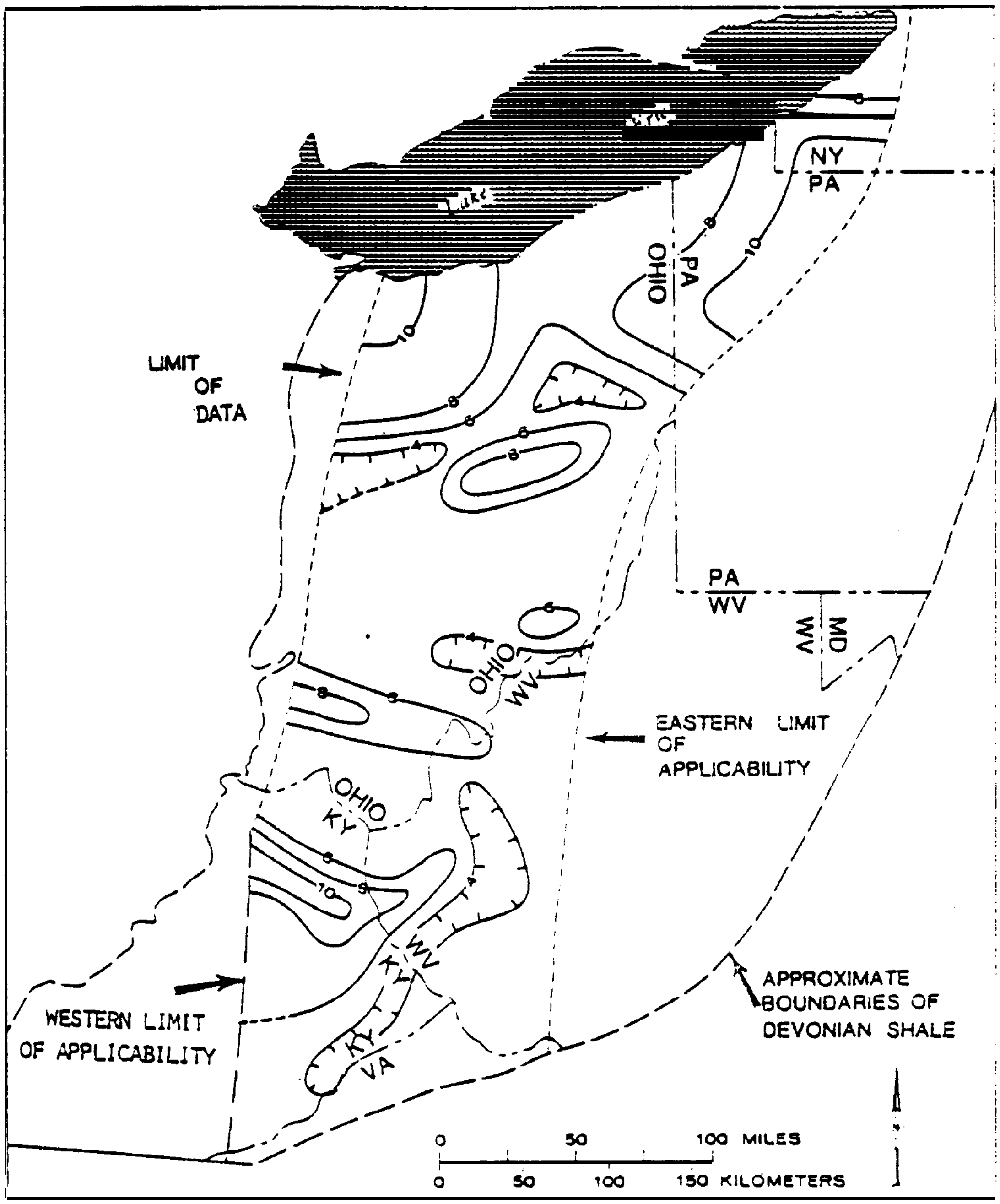

Figure 4.--Organic-matter content (volume percent) of shale having a gamma-ray intensity of 230 API units. An air-filled wellbore and a baseline corresponding to shale containing no organic matter are assumed. Contour interval = 2.0 percent.

1) The minimum organic-matter content required for significant generation of hydrocarbons in shale is' about 0.5 weight-percent carbon (Tissot and Welte, 1978, p. 430), or about 1.7 volume-percent organic matter. The 2-percent boundary thus corresponds to a commonly accepted division between hydrocarbon-source and nonsource rocks.

2) Laboratory analyses of Devonian shale core samples sealed at the well site generally show a change in the relation between movable-gas content and organic-matter content at about 2 to 3 percent organic-matter content by volume, especially in the western part of the basin (G. E. Claypool, personal commun., 1980). Movable-gas content tends to decrease disproportionately in rocks containing less than 2 percent organic matter, and the 2-percent boundary thus corresponds to a change 'in the resource potential of the shale.

DETERMINATION OF ORGANIC-MATTER CONTENT FROM WIRE-LINE LOGS

Formation-Density Log

Organic material in the Devonian shale has a density near 1.0 g/cm^3, whereas the average grain density of the shale minerals is about 2.7 g/cm^3 (Smith and Young, 1964). Changes in organic-matter content thus produce significant changes in formation density, and the organic-matter content of the shale can be estimated from formation density if density variations from other causes are taken into account.

The Devonian shale is treated here as a four-component system consisting of rock matrix, interstitial pores, pyrite, and organic matter. The formation density, ρ, is defined by the densities and fractional volumes of these four components:

$$\rho = \phi_o \rho_o + \phi_p \rho_p + \phi_i \rho_i + (1 - \phi_o - \phi_p - \phi_i) \rho_m \qquad (1)$$

The subscripts o, p, i, and m represent organic matter, pyrite, interstitial pores, and matrix, respectively. To compute organic-matter content from density logs, equation 1 must be reduced to an expression relating formation density, ρ, to organic-matter content, ϕ_o.

Pyrite is a common mineral in the Devonian shale and, because it has a density of 5.0 g/cm^3, it can have a measurable effect upon formation density. The data of Strahl and others (1955) and Brown (1956), and more recent data of J. S. Leventhal (unpub. data, 1980), suggest that pyrite content increases linearly as organic-matter content increases and that this relation can be approximated by the equation:

$$\phi_p = 0.1350, + 0.0078 \qquad (2)$$

By setting $\rho_p = 5.0$ g/cm^3, $\rho_o = 1.0$ g/cm^3, and $\rho_m = 2.69$ g/cm^3 and substituting for ϕ_p according to equation 2, equation 1 becomes:

$$\rho = -1.378\ \phi_o + \phi_i\ (\rho_i - 2.690) + 2.708 \tag{3}$$

Both ϕ_i and ρ_i are unknowns but are assumed constant at a given location. The quantity ρ_B is defined as the formation density if no organic matter is present:

$$\rho_B = \phi_i\ (\rho_i - 2.690) + 2.708 \tag{4}$$

and equation 3, with a rearrangement of terms, can be written:

$$\phi_o = (\rho_B - \rho)\ /\ 1.378 \tag{5}$$

Equation 5 is the basis for estimating organic-matter content from formation-density logs; ρ_B is determined from the density Log at each well location by examining the most dense intervals in the gray-shale sections, which are assumed to contain negligible amounts of organic matter. Thus, the problem of specifying porosity and pore-fluid density is avoided. The empirical determination of ρ_B also has the desirable effect of correcting each density log for calibration bias. Values of ρ_B typically range between 2.67 and 2.72 g/cm^3.

The density-log method was tested by comparing volume-percent organic-matter content estimated from density logs by use of equation 5 with direct laboratory measurements of organic-carbon content in 74 intervals of 12 widely spaced test wells (fig. 3) drilled by DOE contractors. Results provide a comparison of independent methods for determining organic-matter content based on a data set that is reasonably representative of the Devonian shale in the western part of the Appalachian basin. The test intervals range in thickness from 20 to 160 ft (6.1 to 48.8 m) and average about 80 ft (24.4 m). They are defined on the basis of lithologic boundaries in the shale and the availability and sampling intervals of core analyses.

Volume-percent organic-matter content determined indirectly from density logs is compared with laboratory analyses of core samples in figure 5. The overall agreement between the two methods is good, and significant systematic differences as a function of organic-matter content or stratigraphic unit are not apparent.

The distribution of the differences between volume-percent organic-matter content. measured in core samples and that calculated from density logs is shown in figure 6. The distribution has a mean of 0.15 percent and a standard deviation of 1.55 percent, and resembles the normal distribution computed from these parameters.

Although the laboratory analyses of core samples are considered "ground truth" for testing the wire-line methods, the differences shown in figure 6 are not totally attributable to inaccuracies in the density-log method. Laboratory measurements of 'organic-matter'content are subject to errors, and miscorrelation between core and log depths may significantly degrade data comparisons. Also, laboratory analyses of a few samples may not adequately define the average organic-matter content of 20- to 160-ft (6.1-48.8 m) intervals.

Although the absolute precision of the density-log method for estimating organic-matter content is thus not established by comparison to laboratory measurements (figs. 5 and 6), the relative accuracy of the density-log method appears to be sufficient for most geologic applications.

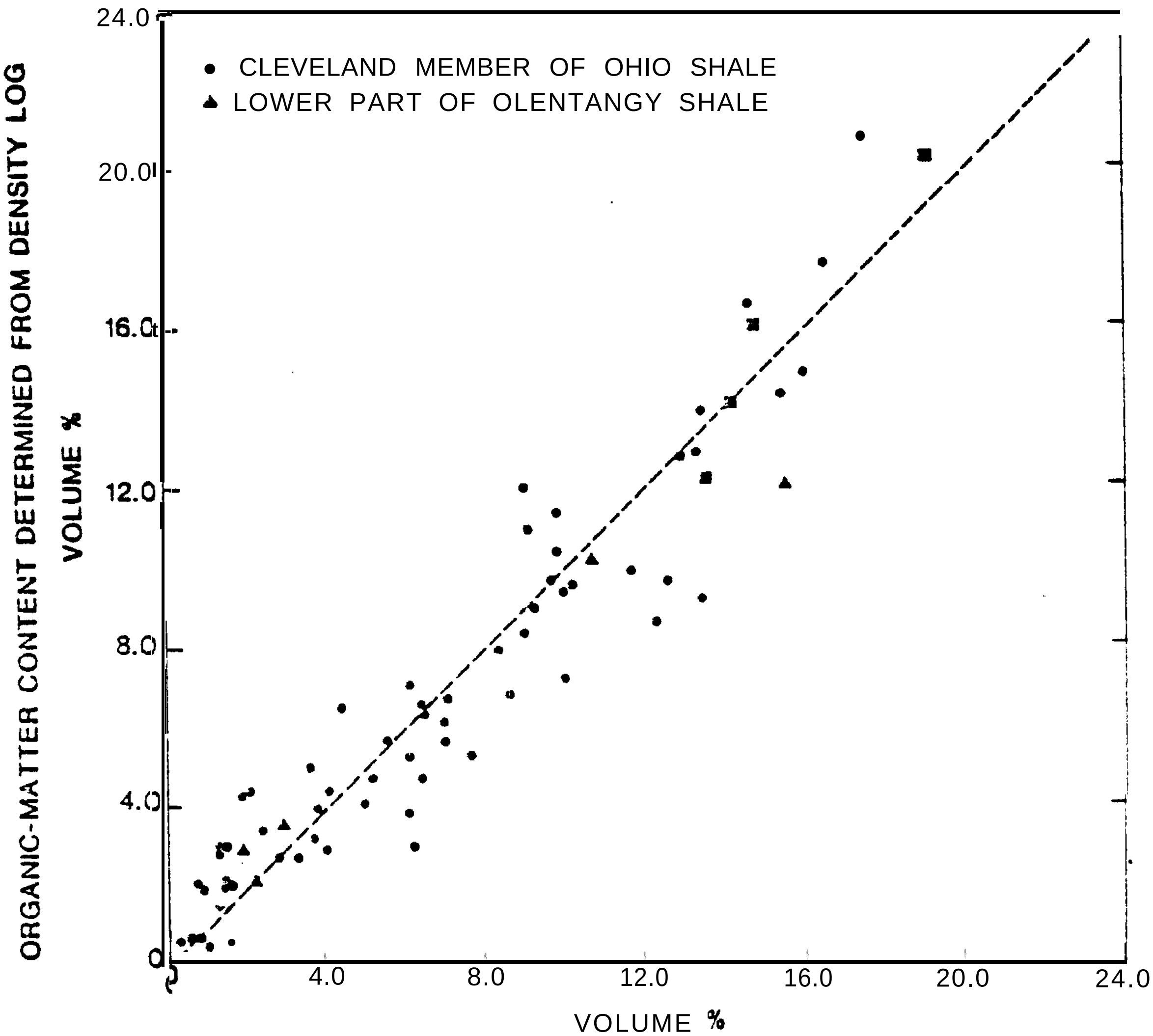

Figure 5.--Comparison of volume-percent organic-matter content in Devonian shales calculated from density logs by use of equation 5 and that measured in core samples. Data are from the 12 test wells represented by circles in figure 3.

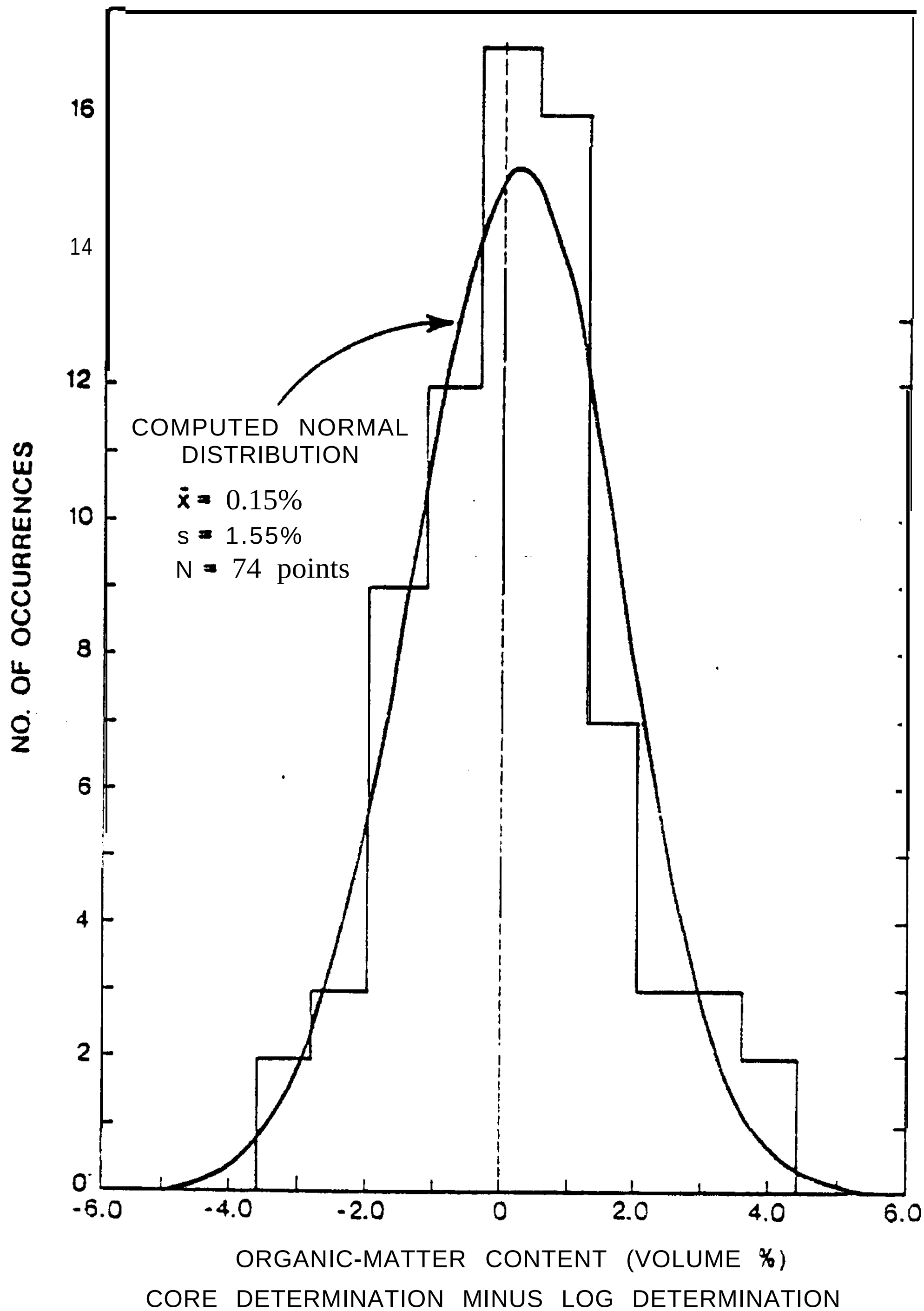

Figure 6.--Distribution of differences between volume-percent organic-matter content measured in core samples and that calculated from density logs.

Gamma-Ray Log

The gamma-ray log records the intensity of natural gamma radiation emitted by a formation. This radiation originates almost entirely from potassium-40 and elements in the uranium 2nd thorium decay series. Prior to 1960, scale settings were generally not standardized, but now most gamma-ray logs are uniformly calibrated in API units. and quantitative analysis of these logs is possible. Because material between the sensor 2nd the formation attenuates gamma-rays, the gamma-ray data used here are from uncased wells 2nd are corrected to empty-hole conditions according to service-company charts.

A gamma-ray log representative of the Devonian shale in the western part of the Appalachian basin is shown in figure 7. Facies rich in organic matter are easily identified 2s intervals of high gamma-ray intensity. If data are averaged to smooth small-scale variations, uranium content is proportional to organic-matter content, but concentrations of the other primary sources of radioactivity-potassium-40 and thorium--are relatively constant at a given location (McKelvey and Nelson, 1950; Swanson, 1956; Conant and Swanson, 1961; Leventhal and Goldhaber, 1978). Consequently, variations in gamma-ray intensity in a given well are due mainly to changes in uranium concentration.

The correlation between gamma-ray intensity and organic-matter content observed in Devonian shale in most of the western part of the Appalachian basin reflects the association of uranium with organic matter. Factors controlling this association probably include:

1) Uranium content of seawater at the time of deposition

2) Type of organic matter deposited

3) Water chemistry near the water-sediment interface

4) Rate of sediment deposition.

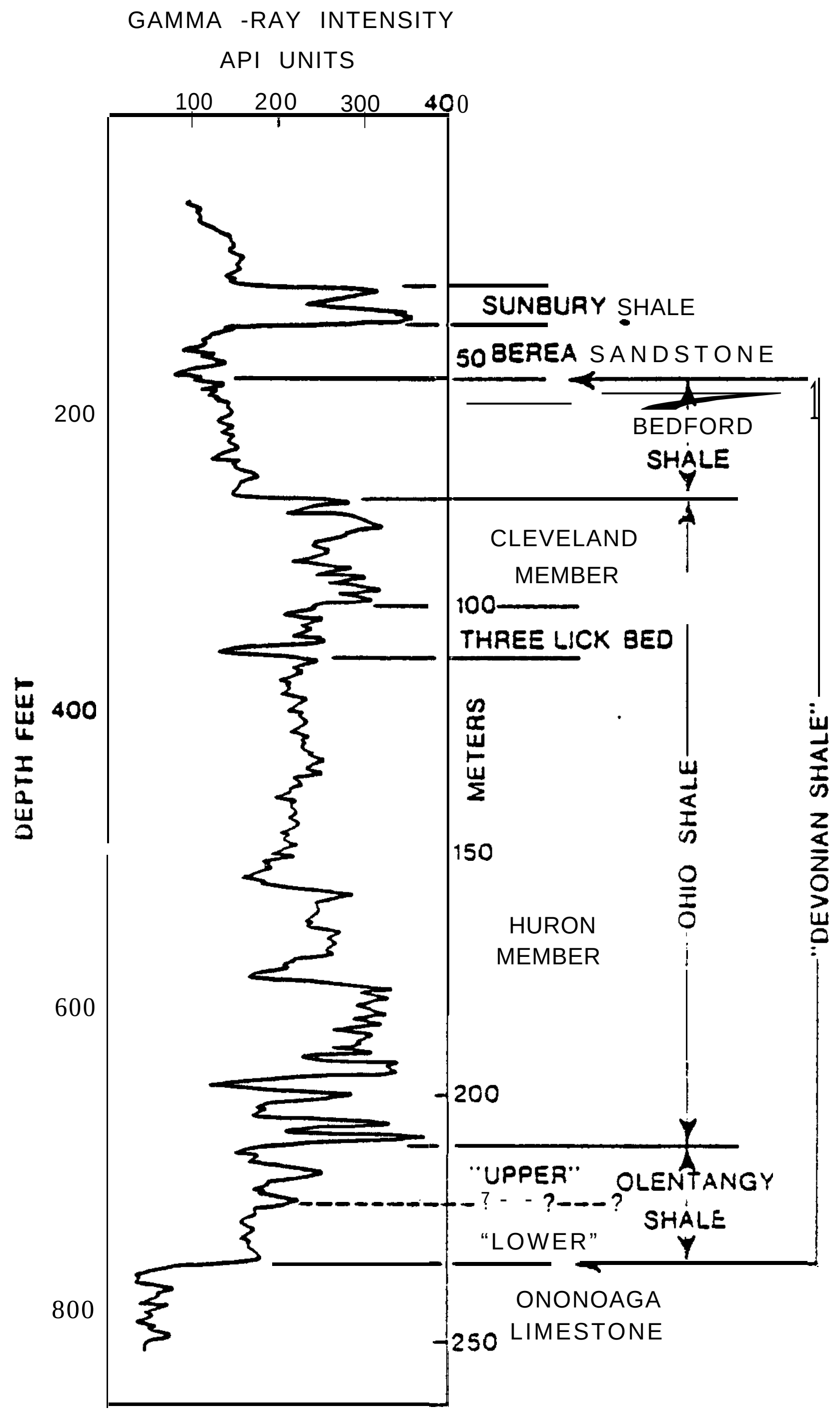

Figure 7.--Gamma-ray log from Pike County, Ohio, showing features typical of the Devonian shale in the western part of the Appalachian basin (adapted from Wallace and others, 1977).

A consistent relation between gamma-ray intensity and organic-matter content makes quantitative interpretation of the gamma-ray log possible and suggests that these factors remained relatively constant at a given location.

Qualitative estimates of relative concentrations of organic matter and consequent geologic inferences can be made from visual inspection of gamma-ray logs; however, the value of the gamma-ray measurements is significantly increased by quantifying, where possible, the relation between gamma-ray intensity and organic-matter content.

The slope of the crossplot of gamma-ray intensity and formation density is assumed constant at a given location and is defined as A (API units/(g/cm^3)), so that:

$$(\gamma_B-\gamma) = A\,(\rho_B-\rho) \tag{6}$$

where γ is the gamma-ray intensity (API units), ρ the formation density (g/cm^3), and γ_B and ρ_B the gamma-ray intensity and formation density if no organic matter is present. Both γ_B and ρ_B are assumed constant at a given location. Substituting for $(\rho_B-\rho)$ in equation 5 yields an expression relating the fractional volume of organic matter, ϕ_o, to gamma-ray intensity:

$$\phi_o = (\gamma_B - \gamma) / 1.378A \tag{7}$$

Equation 7 is the basis of the gamma-ray method for estimating organic-matter content in the Devonian shale.

The slope of the crossplot of gamma-ray intensity and formation density, A, and the gamma-ray intensity if no organic matter is present, γ_B, can be determined at a given location from regional maps of these quantities. Gamma-ray and density logs from the well locations shown in figure 3 were used to compile maps of A (fig. 8) and γ_B (fig. 9). The number and spacing of wells are sufficient to define A and γ_B regionally, but the maps would be improved locally by wire-line data from additional locations.

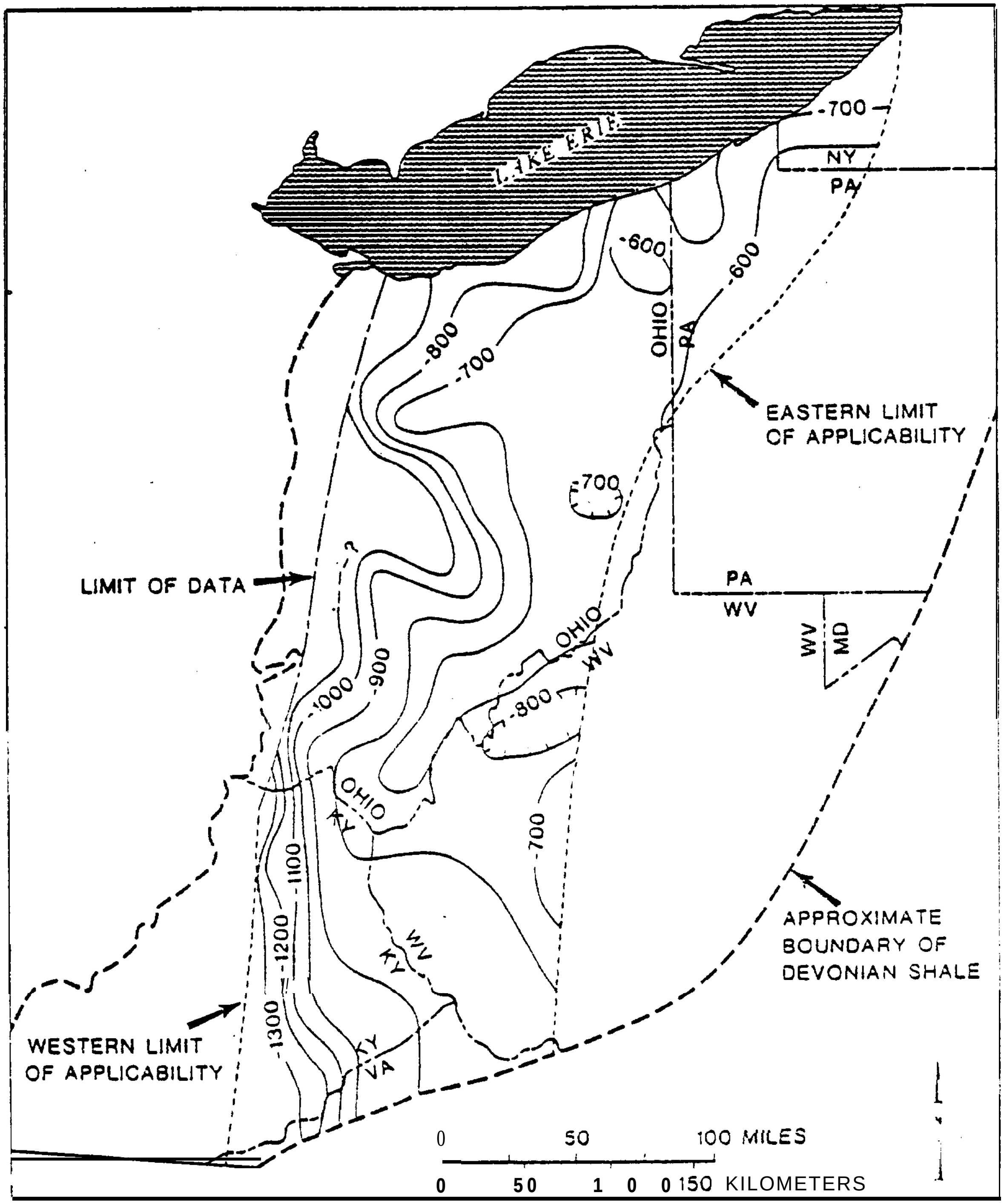

Figure 8.--Slope of the crossplot of gamma-ray intensity and formation density, A. Gamma-ray intensity is corrected to empty-hole conditions. Contour interval = 100 API units/(g/cm^3).

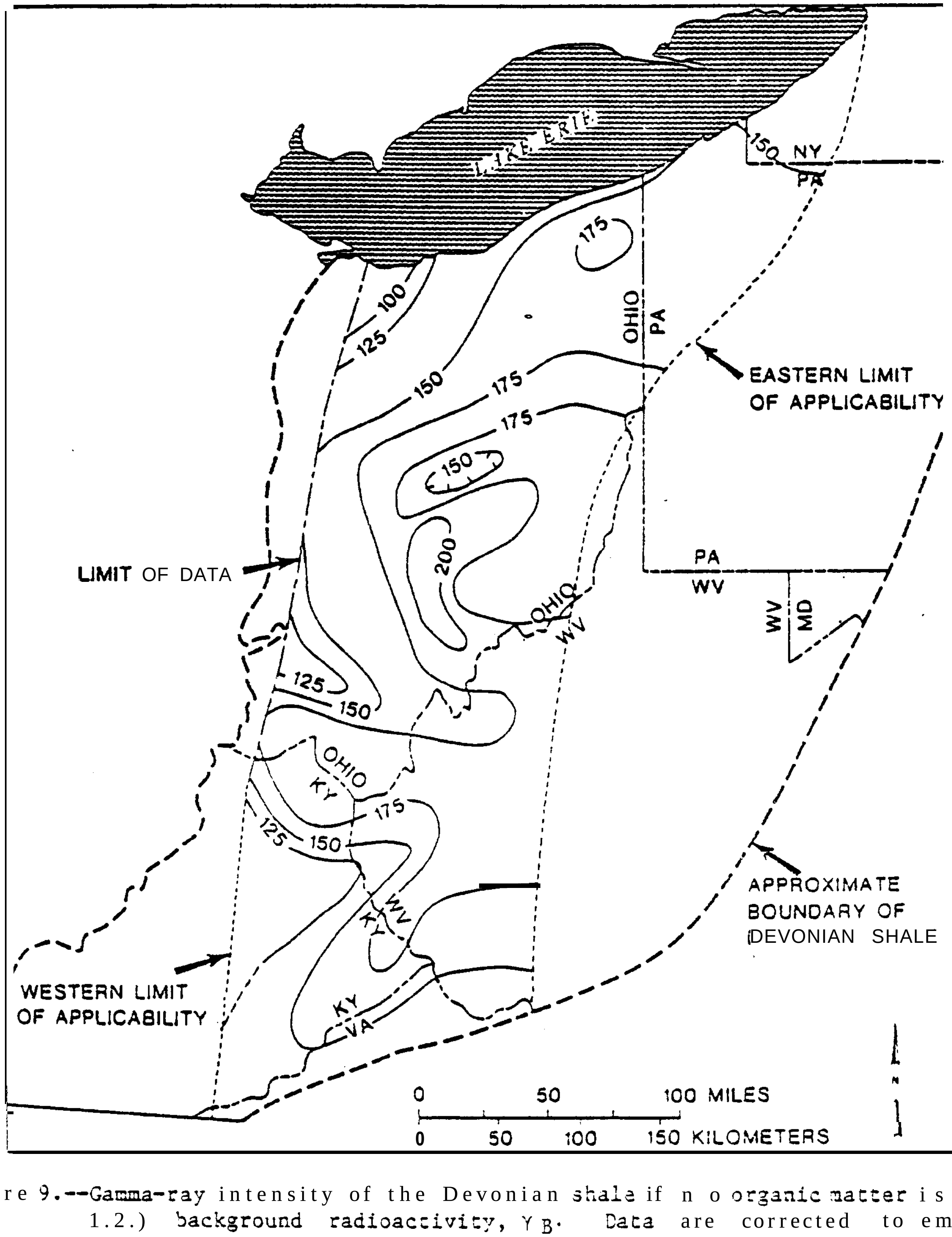

figure 9.--Gamma-ray intensity of the Devonian shale if no organic matter is present, 1.2.) background radioactivity, γ_B. Data are corrected to empty-hole conditions. Contour interval = 25 API units.

The slope of the crossplot (fig. 8) is negative because gamma-ray intensity increases as formation density decreases. Values of A vary by more than a factor of two, showing that the level of radioactivity associated with a given concentration of organic matter varies regionally and that the subjective comparison of gamma-ray logs from different parts of the basin can be misleading.

The eastward decrease in the absolute value of the 'crossplot slope (fig. 8) corroborates the observations (e.g., of Schweitering, 1970, p. 7; Patchen, 1977) that Devonian black shale facies become less radioactive to the east although retaining about the same color. The likely effect of an increase in the density of organic matter due to the general increase in thermal maturity to the east (Claypool and others, 1978;. Harris, 1978) is a slight eastward increase in the absolute value of the crossplot slope, which is counter to the observed trend.

Figure 9 shows the average gamma-ray intensity of the Devonian shale if the effect of radioactivity associated with organic matter is subtracted from total formation radioactivity. This residual or background radioactivity, γ_B, tends to increase to the east, although the trend is distorted by local and semi-regional anomalies. Values of γ_B range between 100 and 200 API units in the mapped area (fig. 9), so that differences in the level of radioactivity shown by gamma-ray logs from different parts of the basin are not due solely to differences in organic-matter content.

The gamma-ray method was tested by comparing volume-percent organic-matter content computed from gamma-ray logs by use of equation 7 with laboratory measurements of organic-carbon content in the same 74 intervals and 12 wells used to evaluate the density-log method. Values of A and γ_B were obtained from figures 8 and 9. Because the data set for figures 8 and 9 includes data from the 12 test wells, the values of A and γ_B used in the comparison calculations are probably more accurate than could be expected in general application.

Volume-percent organic-matter content determined indirectly from gamma-ray logs is compared with laboratory analyses of core samples in figure 10. The overall agreement between the two methods is fairly good. In general, the gamma-ray intensity of the shale can be used as a quantitative indicator of organic-matter content.

Some of the scatter in figure 10 does not appear'to be random. Organic-matter content estimated by the gamma-ray method is slightly but consistently higher than laboratory measurements for intervals in which laboratory-determined organic-matter content is less than about 2 percent by volume. This effect in intervals poor in organic matter is of minor significance from a practical viewpoint of resource evaluation. It is noted here because it may imply that the "gray" shales contain relatively more terrestrially derived organic matter, with a greater than average affinity for uranium, than do the shales richer in organic matter, as suggested by the δC^{13} measurements of Potter and others (1980, p. 42).

Intervals of greatest difference between the gamma-ray method and laboratory measurements tend to plot below the line of ideal agreement. The gamma-ray method significantly underestimates the organic-matter content of some intervals, a majority of which represent the Cleveland Member of the Ohio Shale and the lower part of the Olentangy Shale. These units are anomalous in that they are not as radioactive as other Devonian shales having similar organic-matter content.

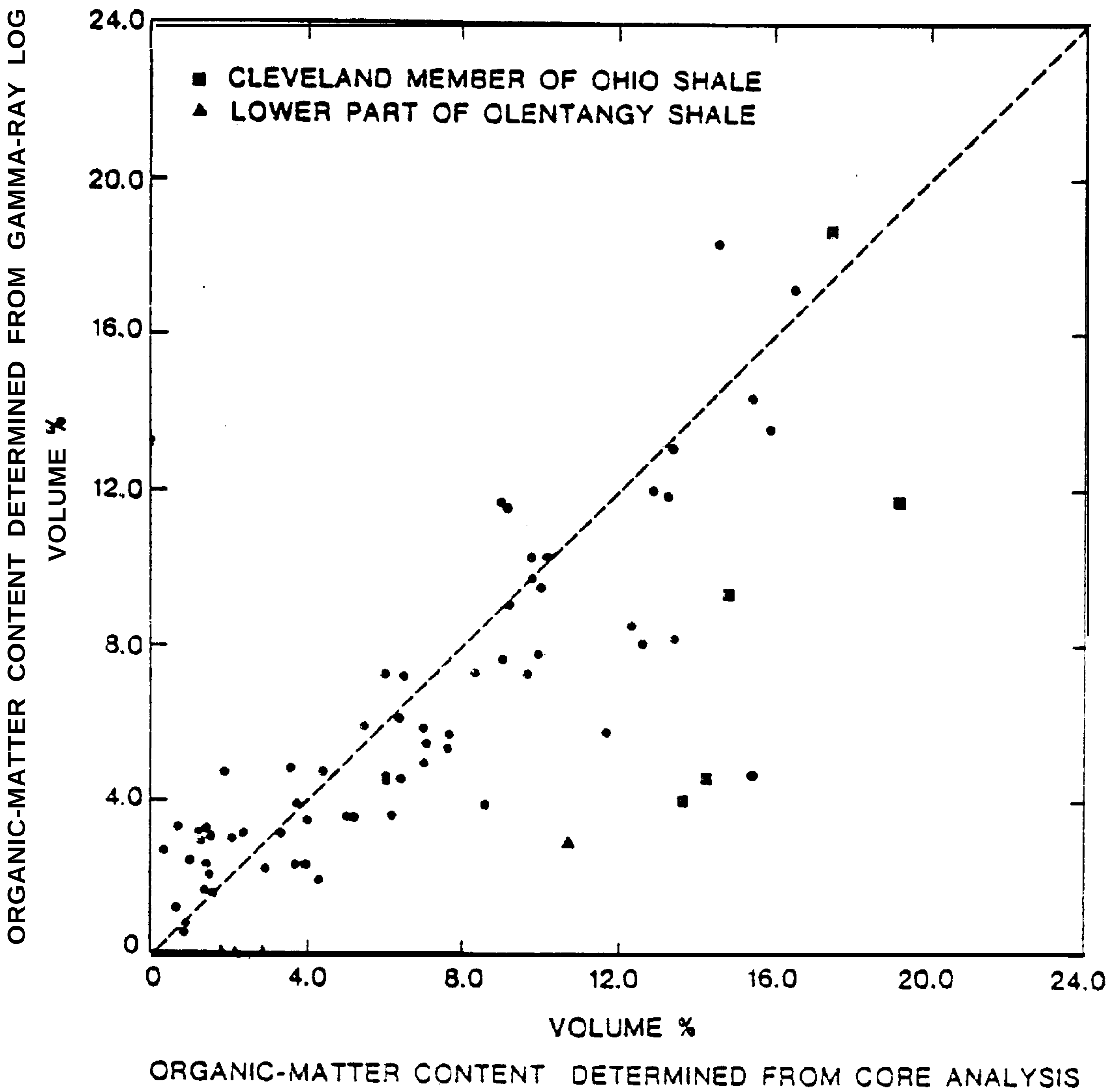

Figure 10.--Comparison of volume-percent organic-matter content in Devonian shales calculated from gamma-ray logs by use of equation 7 and that measured in core samples. Data are from the 12 test wells represented by circles in figure 3.

The Cleveland Member of the Ohio Shale is present along the western edge of the basin from Lake Erie to Tennessee, and is readily identified on gamma-ray logs as the uppermost interval of high radioactivity in the Ohio Shale (fig. 7). The Olentangy Shale is comprised of an upper and lower part (fig. 7) separated by an unconformity (Tillman, 1970; Wallace and others, 1977). Only the lower part, which can be identified on gamma-ray logs in the western part of the basin by its low relative radioactivity and stratigraphic position at or near the base of the Devonian shale sequence, is anomalous in its relation between radioactivity and organic-matter content.

The distribution of the differences between volume-percent organic-matter content measured in core samples and that calculated from gamma-ray logs, except differences for intervals from the Cleveland Member of the Ohio Shale and the lower part of the Olentangy Shale, is shown in figure 11. The distribution has a mean of 0.44 percent and a standard deviation of 1.98 percent, and resembles the normal distribution computed from these parameters.

As discussed in the preceding section, the absolute precision of the gamma-ray method is not astablished by comparisons to laboratory measurements (figs. 10 and 11) because of uncertainty associated with rhe laboratory data as well as with the wire-line interpretations. However, the relative accuracy of the gamma-ray method for estimating organic-matter content is sufficient for most geologic applications if the method is not applied to the Cleveland Member of the Ohio Shale or the lower part of the Olentangy shale.

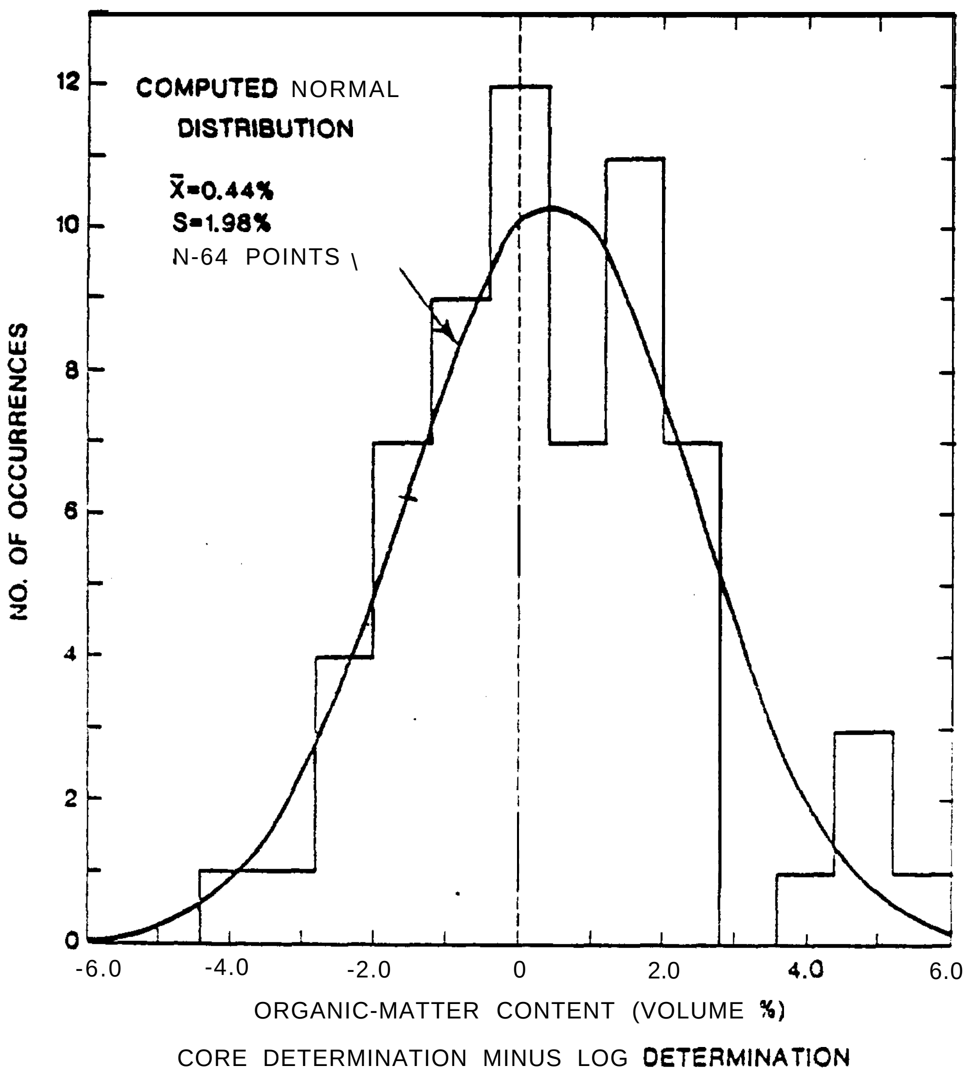

Figure 11.--Distribution of differences between volume-percent organic-matter content measured in core samples and that calculated from gamma-ray logs. Data from the Cleveland Member or' r-he Ohio Shale and the lower part of the Olentangy Shale are excluded.

Comparison of Density-Log and Gamma-Ray Methods

The density-log method for estimating organic-matter content is more widely applicable and is slightly more accurate than the gamma-ray method. The systematic differences of figure 10 are not apparent in figure 5. The density-log method can be applied to the entire Devonian shale section. The principal advantage of the gamma-ray method is its use of more readily available data.

The underlying reason for the better accuracy of the density-log method is that density, unlike radioactivity, is an inherent property of organic matter. Organic matter in the Devonian shale has a relatively Low specific gravity and the effect upon formation density is certain; however, the radioactivity of the organic matter depends on the association of uranium with organic aatter, which in turn depends on potentially variable physical and geochemical conditions at the time of deposition.

The validity of the simplifications and conditions assumed in the derivation of equations 5 and 7 is best tested by the comparisons to core analyses shown in figures 5, 6, 10 and 11. These comparisons indicate that the model for the distribution of radioactive elements in the shale is not appropriate for the Cleveland Member of the Ohio Shale and the lower part of the Olentangy Shale. With these exceptions, deviations from the assumed geologic model do not render the wire-line methods for determining organic-matter content ineffective.

CLEVELAND MEMBER OF THE OHIO SHALE

The Cleveland Member of the Ohio Shale is not as radioactive as other ·onian shales of similar organic-matter richness, and organic-matter content iputed by the gamma-ray method is likely to be too low (fig. 10). Because : Cleveland Member is very rich In organic matter and may thus have greater ın average natural-gas potential, its anomalous radioactivity is of :ticular interest.

The Cleveland Member occurs as a linear zone, nearly parallel to the tcrop of Devonian shale, in the western half of the study area (fig. 12). e deviation of its gamma-ray intensity from normal varies as a function of cation. The radioactivity of the upper 40 Et (12.2 m) of the Cleveland mber is about 200 API units below normal in southeastern Kentucky but is ss than 40 API units below normal in the northern part of the basin (fig.). The deviation from normal radioactivity also appears to decrease from :st to east and from the top to the base of the unit, but more wire-line data ·e needed to quantify these observations.

The author is not aware of the documentation of any other anomalous ıysical or geochemical properties in the Cleveland Member. Lamey and ıilders (1977) found no significant compositional differences in the organic atter of the Cleveland Member in the Perry County, Kencucky, test well (fig- , well 6), and carbon-isotope measurements by Potter and others (1980), which ay reflect organic-matter composition, indicate that δC^{13} values of the leveland Member are typical of the Devonian shale as a whole (fig. 14). reservation of relatively large amounts of organic matter in the Cleveland lember implies an anoxic depositional environment not unlike that of other black" shales in the Devonian sequence. Thus, one can speculate on the :easons for the anomalous radioactivity of the Cleveland Member in terms of :he factors controlling the association of uranium with organic matter, but :he true causes are not clear.

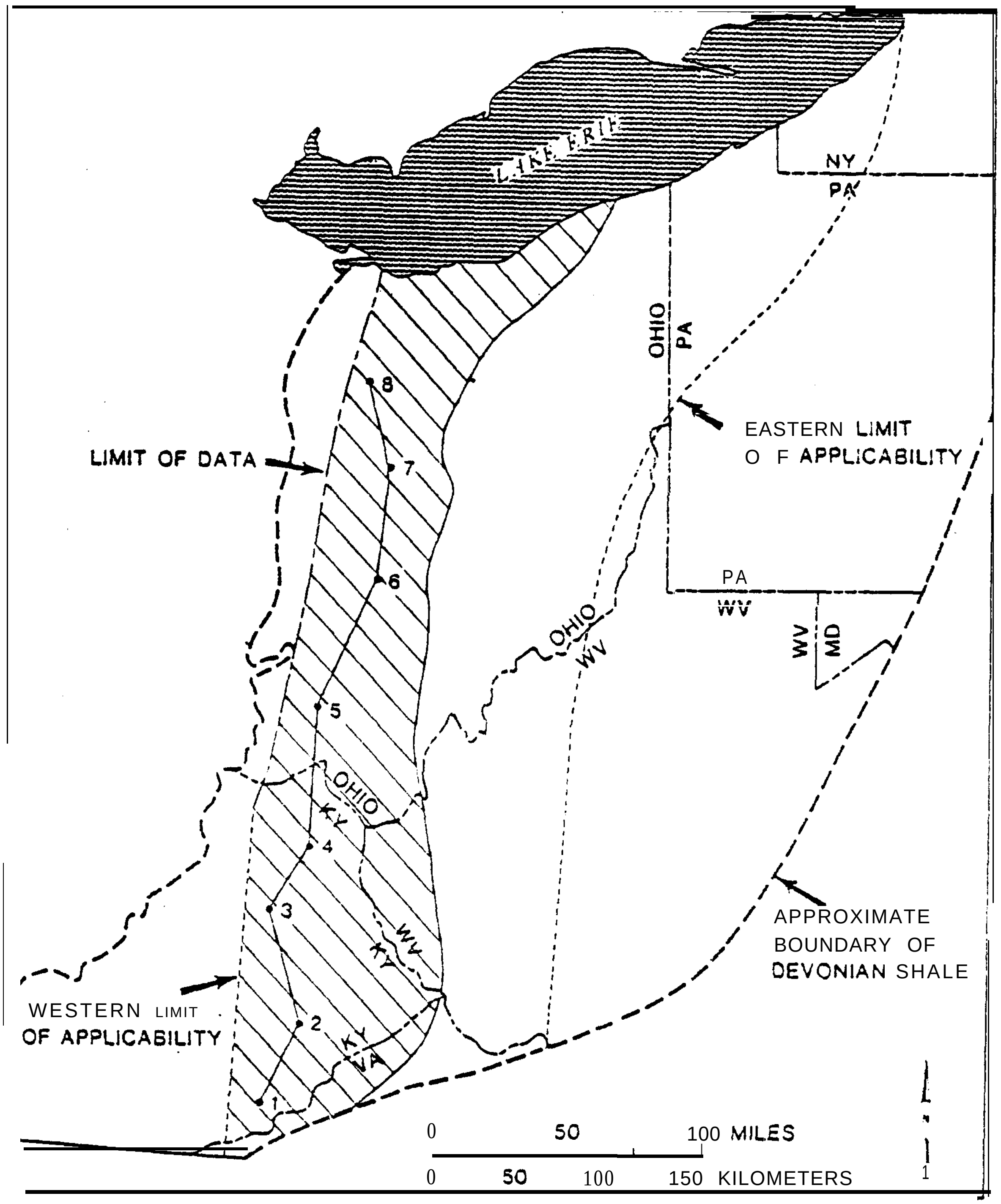

Figure 12.--Distribution (hachured) of the Cleveland Member of the Ohio Shale in the studv area (Lewis and Schwietering, 1971; Provo, 1976), and Line of the cross section shown in figure 13.

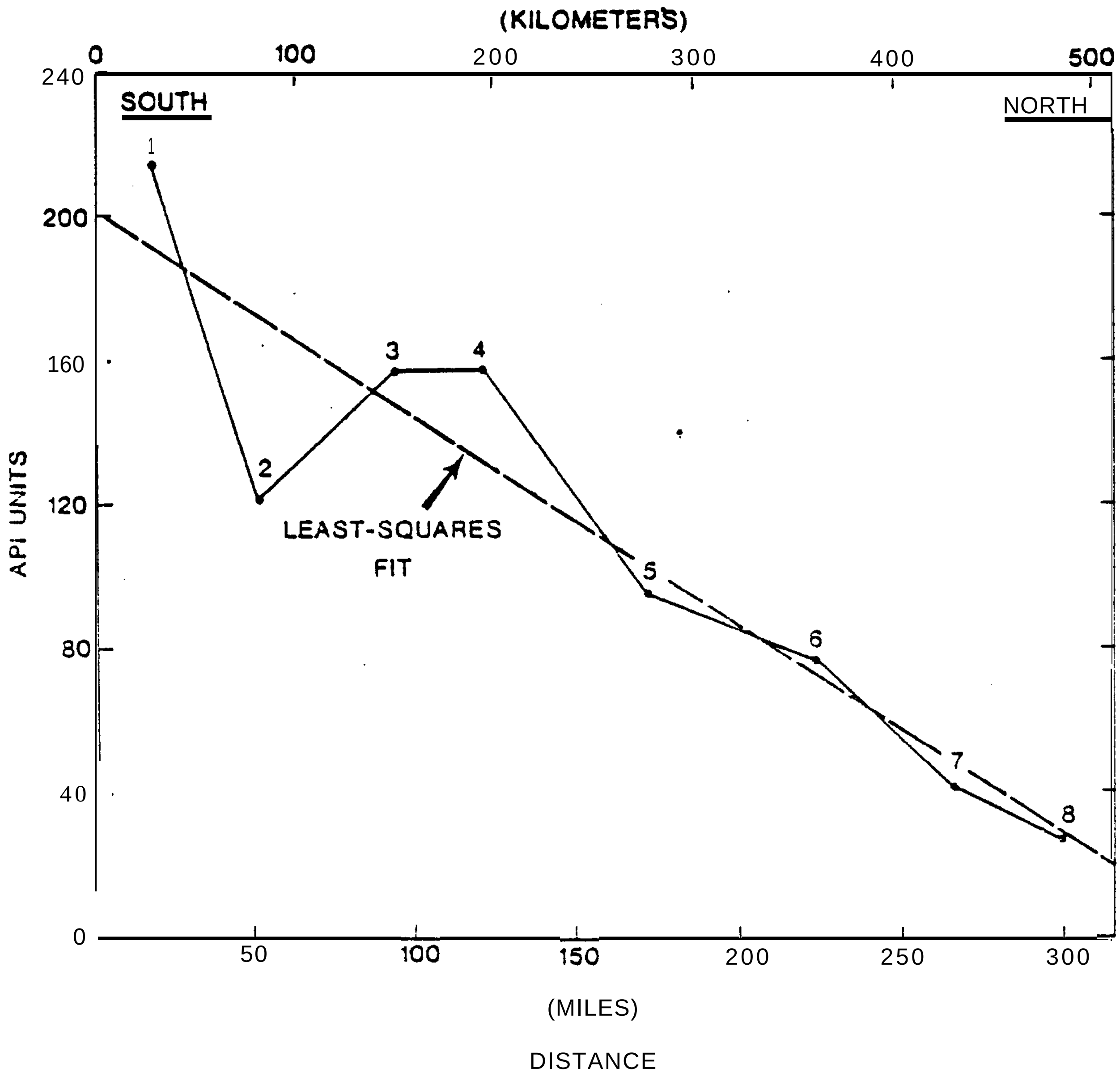

Figure 13.--Number of API units that data for the upper 40 ft (12.2 m) of the Cleveland Member of the Ohio Shale plot below the regression line of the gamma-ray versus density crossplot. The Cleveland Member is not as radioactive as other Devonian shales containing similar amounts of organic matter, but the difference becomes progressively smaller to the north. The line of the section is shown in figure 12.

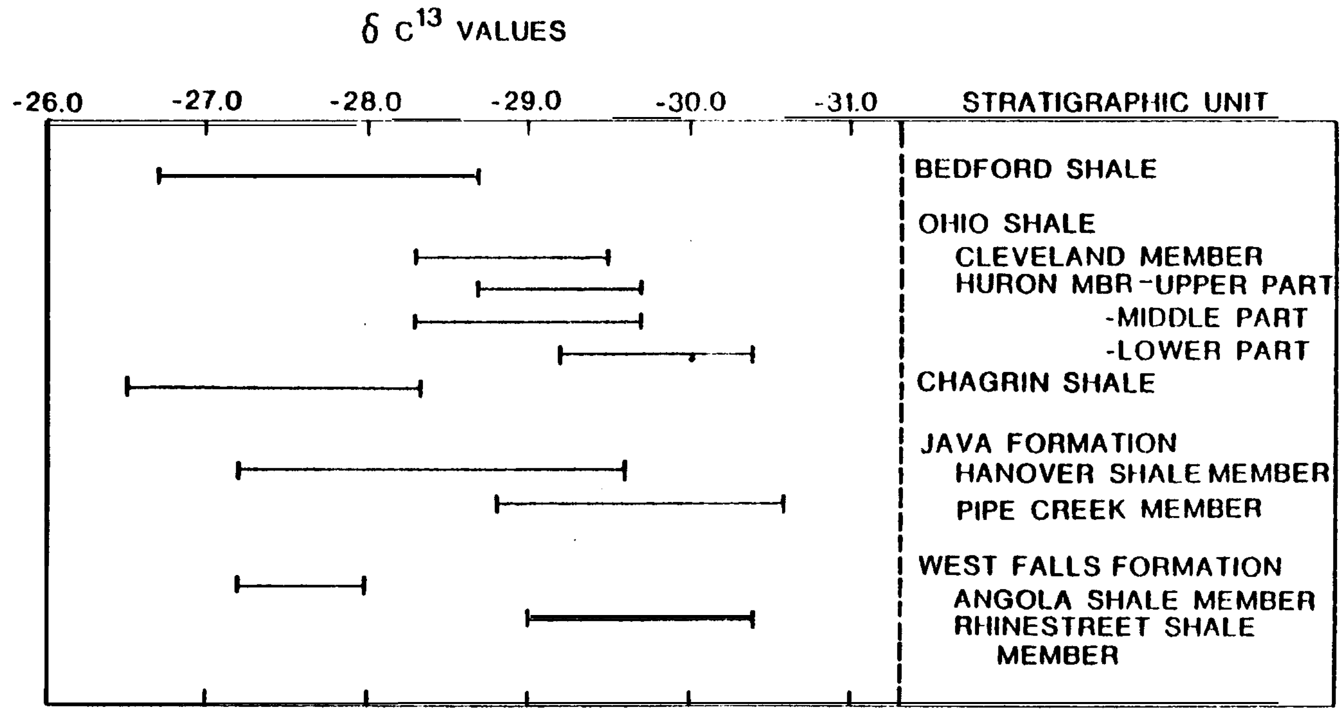

Figure 14.--Carbon-isotope values for Devonian shales of the Appalachian basin, showing that values for the Cleveland Member of the Ohio Shale are not atypical. Data are from Potter and others (1980, p. 41).

REGION OF APPLICABILITY

To be of practical significance, the wire-line methods for estimating organic-matter content should be applicable in a large area of the Appalachian basin. Available data indicate that the methods are valid in an area of about 50,000 mi^2 (130,000 km^2) in the western part of the Appalachian basin (fig. 3).

Within this area, wire-line data smoothed by averaging vertical intervals of 20 to 40 ft (6.1-12.2 m), to reduce scatter due to instrument, error and small-scale geologic variations, show a linear relation between density and gamma-ray intensity. This linear relation is a basic part of the gamma-ray method (equation 6), and confirms the fundamental assumption of the density-log method that density variations are caused by variations in organic-matter content, because factors such as porosity or mineralogic variations that might change formation density would not significantly affect the garmna-ray intensity. Thus, quantitative interpretation of the gamma-ray log in terms of organic-matter content requires a predictable covariance between gamma-ray intensity and formation density, and doubt is cast on the applicability of the density-log method if the crossplot is not linear.

A linear relation between gamma-ray intensity and formation density such as that shown in figure 15 is typical of the Devonian shale in the region of applicability. This representative crossplot has a correlation coefficient of -0.86 and a standard deviation of density about the regression line of 0.021 g/cm^3.

In east-central Kentucky, the correlation between gamma-ray intensity and formation density weakens or disappears along a line closely paralleling the 250-ft (76-m) Devonian shale isopach (fig. 16). West of the limit of applicability in Kentucky, the typical gamma-ray versus density crossplot is random (fig. 17).

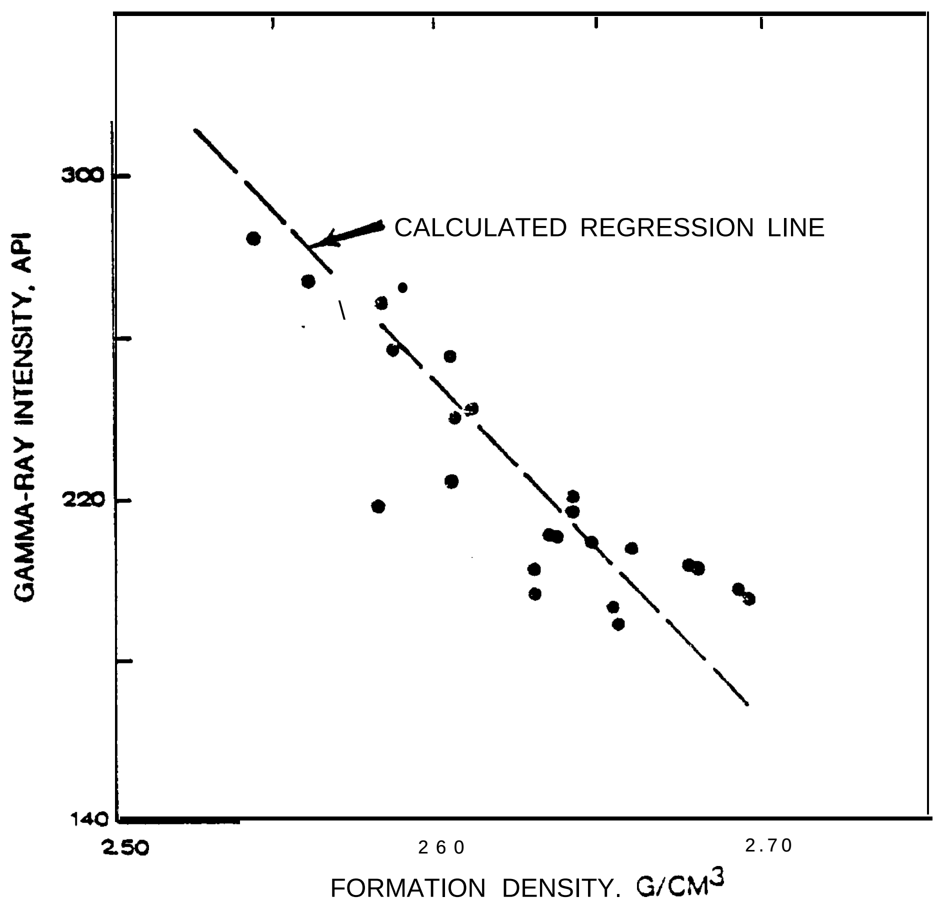

Figure 13.--Wire-line data from Jackson County, West Virginia (fig. 3, well 3), averaged over 20-ft (6.1-m) intervals, showing the strong linear relation between density and gamma-ray intensity that is typical of the Devonian shale in most of the western part of the Xppaiachian basin.

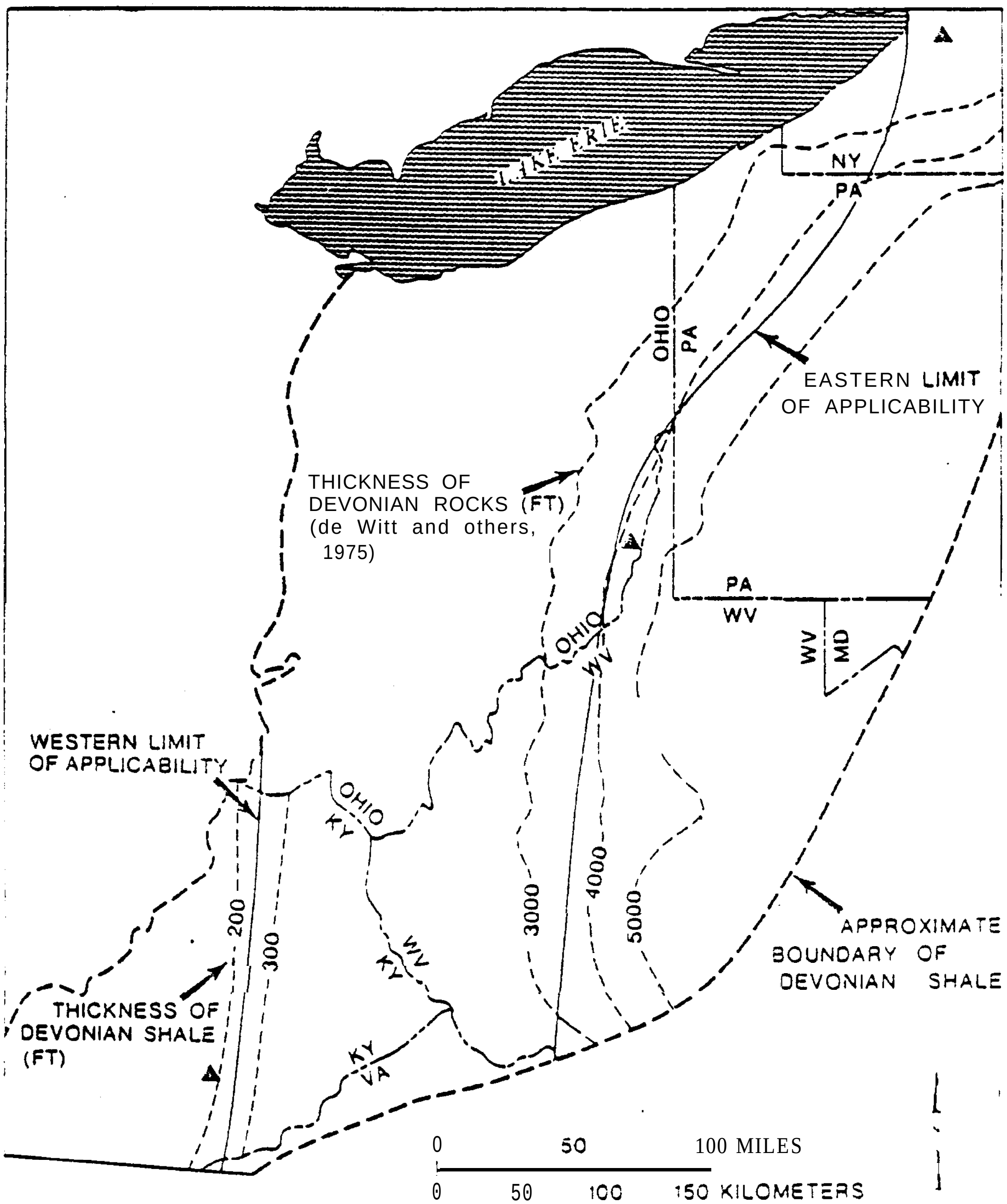

Figure 16.--Limits of applicability marking the eastern and western boundaries of the region of significant correlation between gamma-ray intensity and formation density, and their relation to thickness of the Devonian section. Triangles locate wells where data of figures 17-19 were obtained.

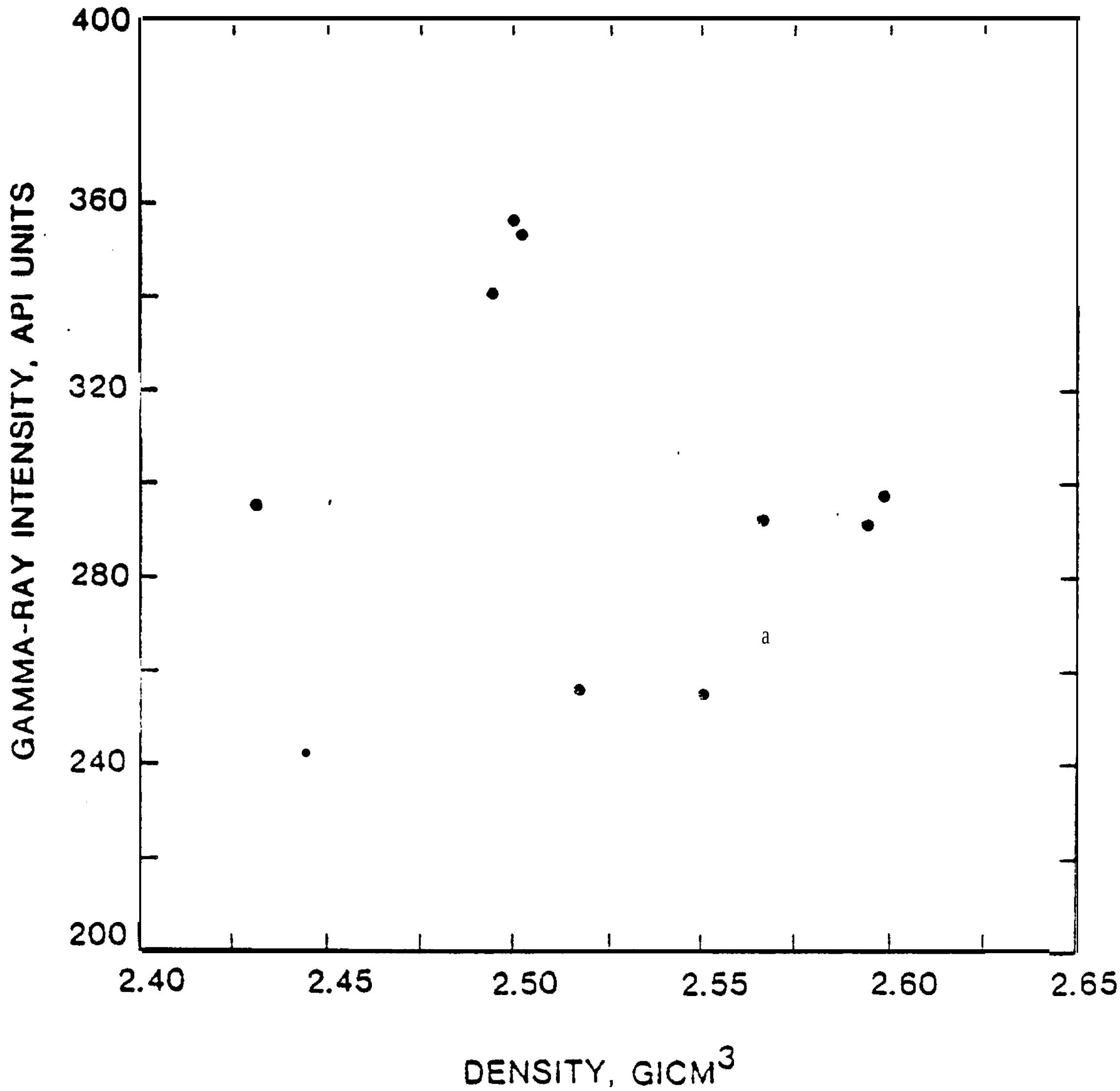

Figure 17.--Wire-line data from Clay County, Kentucky (located by triangle on figure 16), averaged over 20-ft (6.1-m) intervals, showing lack of correlation between gamma-ray intensity and formation density.

The correlation between gamma-ray intensity end formation density also weakens or disappears in the eastern part of the basin. The eastern limit of applicability (fig. 16) roughly parallels the 4,000-ft (1,219-m) total-Devonian-sequence isopach as shown by de Witt and others (1975).

East of the limit of applicability in New York, a representative crossplot of gamma-ray intensity and formation density (fig. 18) has a random character somewhat like that of the crossplot typical of central Kentucky. Farther south, however, the typical crossplot east of the limit of applicability (fig. 19) has a different appearance, with gamma-ray intensity remaining nearly constant as formation density decreases. Only the Marcellus Shale at the base of the Devonian shale sequence (represented by a single point in the upper left corner of figure 19) has a gamma-ray intensity. significantly above the background.

DISTRIBUTION OF ORGANIC MATTER

In this section, the distribution of organic matter in the organic-matter-rich facies of the Devonian shale in the western part of the Appalachian basin is characterized by using data derived from formation-density wire-line logs; the boundary between organic-matter-rich and organic-matter-poor facies is defined as 2 percent organic-matter content by volume. Several zones of organic-matter-rich shale of significant thickness are present in the western part of the basin, but organic-matter-content data from these zones are aggregated here without stratigraphic differentiation. Wire-line data are from the well locations of figure 3.

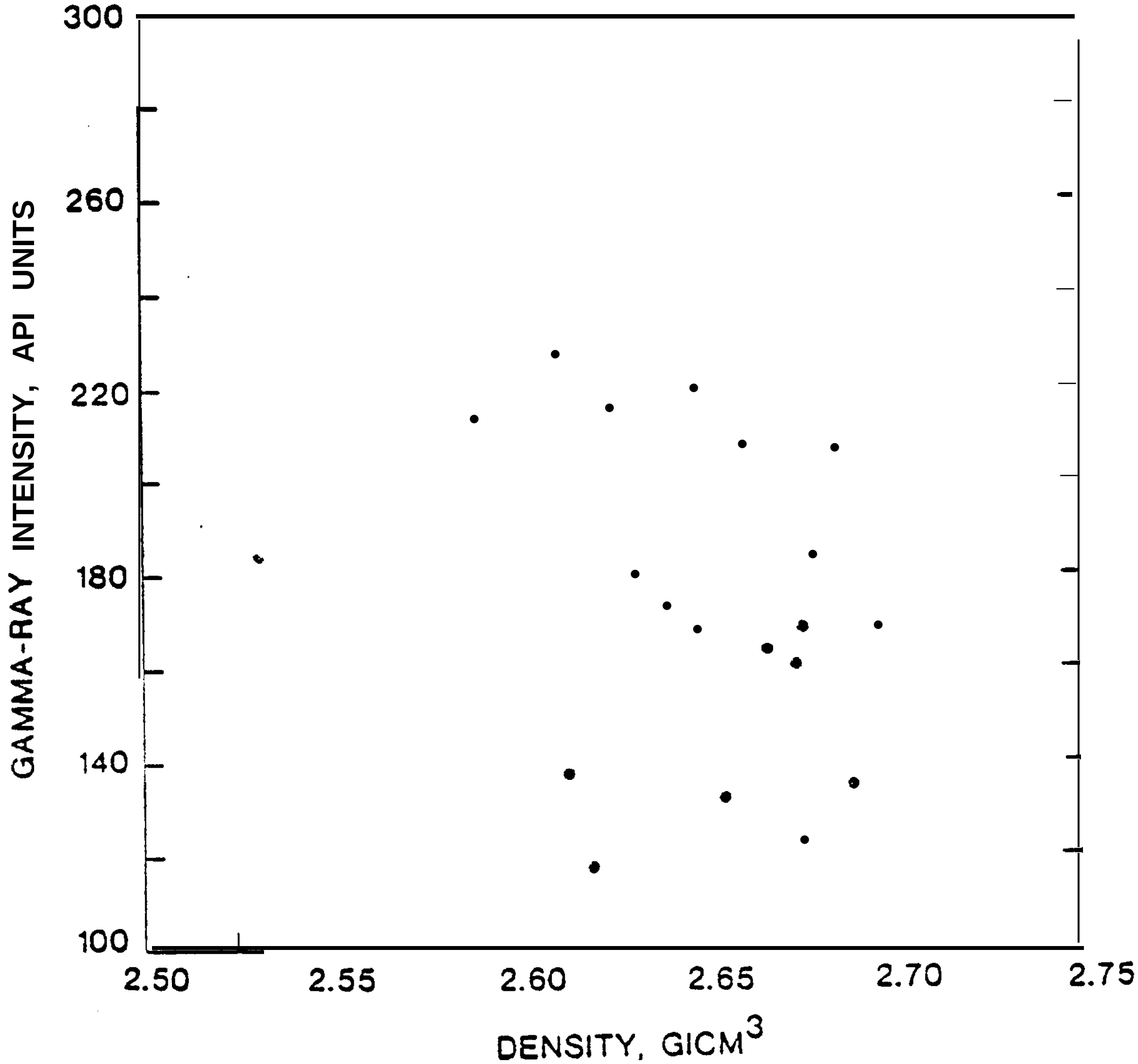

Figure 18.--Wire-line data from Erie County, New York (located by triangle on figure 16), averaged over 40-ft (12.2-m) intervals, showing lack of correlation between gamma-ray intensity and formation density.

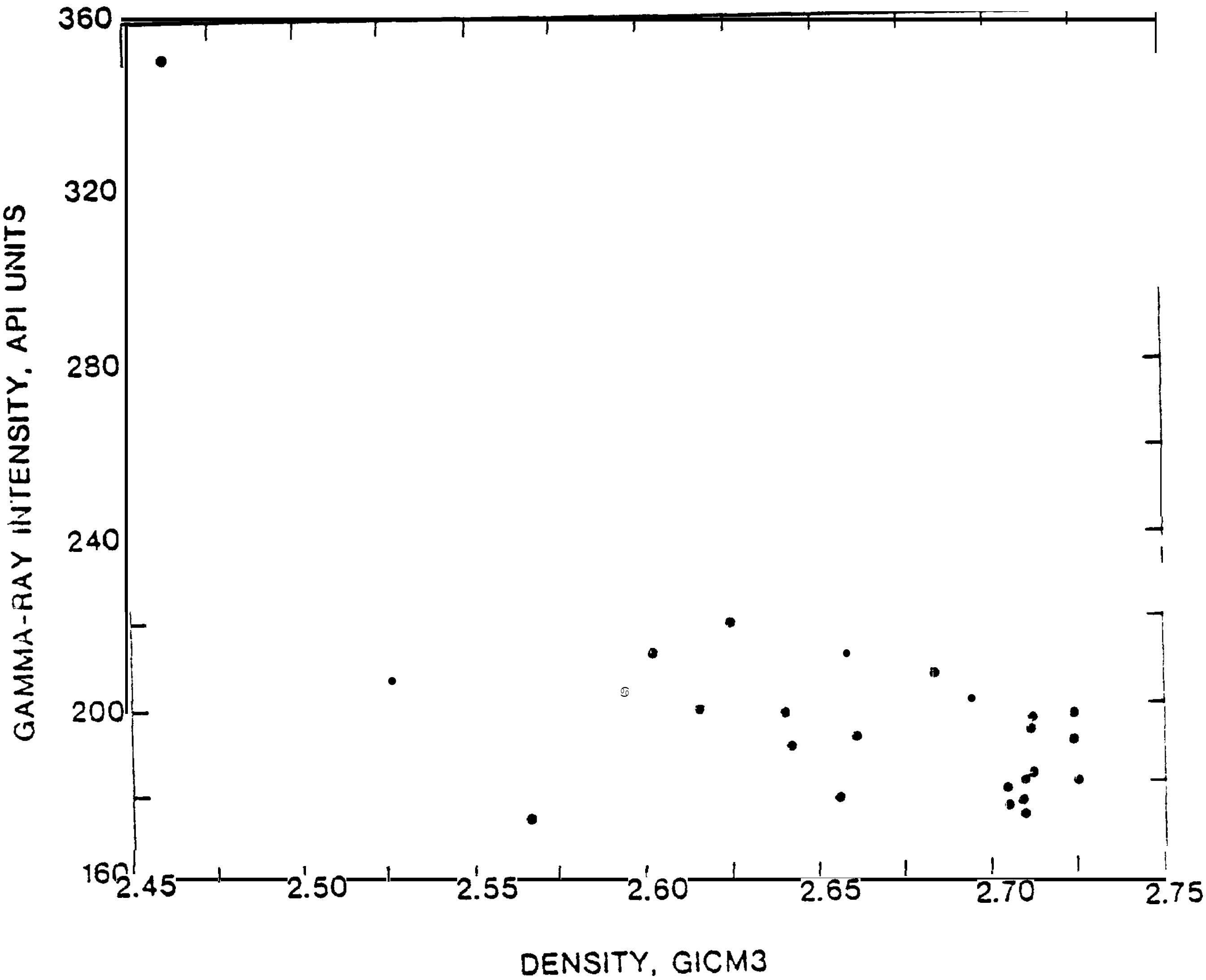

Figure 19.--Wire-Line data from Belmont County, Ohio (located by triangle on figure 16), averaged over 40-ft (12.2-m) intervals, showing lack of correlation between gamma-ray intensity and formation density.

Thickness of Organic-Matter-Rich Facies

The thickness of organic-matter-rich facies determined from formation-density logs (fig. 20) ranges from less than 300 ft (91 m) in east-central Kentucky to 1,000 ft (305 m) along the Kentucky-West Virginia border. Local maxima occur along a north-trending crest that is the dominant regional feature of figure 20.

The north-trending crest is equivalent to the western black-shale belt of Harris and others (1978). They noted that the western black-shale belt is separated from an eastern black-shale belt (east of the eastern limit of applicability shown in figure 20) by a transition zone of relatively thin organic-matter-rich rocks. Lobes extending through the transition zone form connecting links between the western and eastern belts. Three east-trending ridges at the eastern edge of the mapped area of figure 20 may be connecting lobes.

The thickness of organic-matter-rich Devonian shale facies determined by de Witt and others (1975) on the basis of the color of well cuttings (fig. 21) is generally less than the thickness shown in figure 20 because de Witt and others' data are based on a boundary between organic-matter-rich and organic-matter-poor shales that is probably equivalent to about 4 percent organic matter by volume, whereas the data of figure 20 are based on a boundary of 2 percent. Although the general trends of the two maps are similar, differences in facies thickness and location of anomalies reflect the inclusion in figure 20 of shale having relatively light color values.

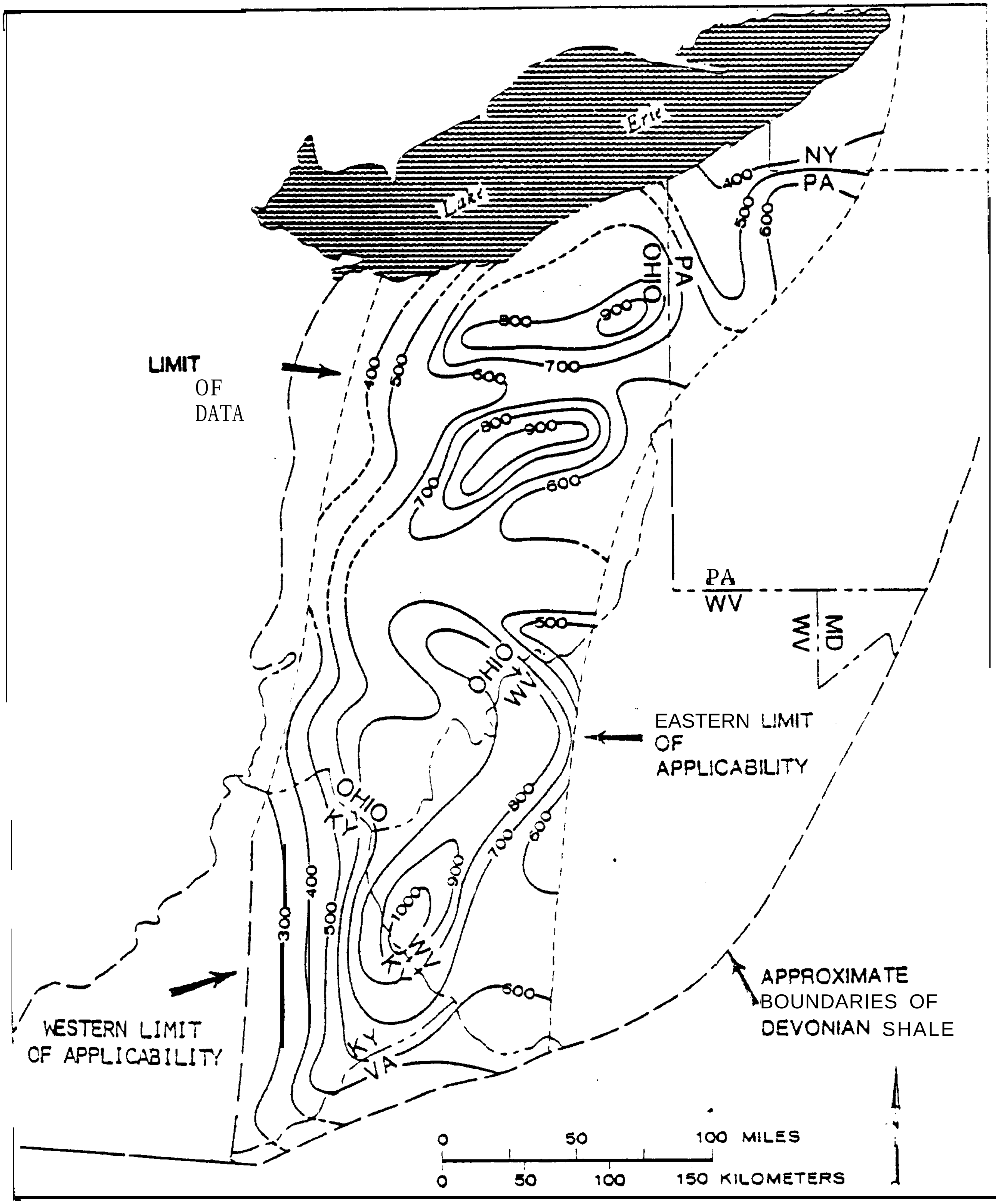

Figure 20.--Thickness (ft) of organic-matter-rich Devonian shale facies determined from formation-density logs; organic-matter-rich facies are defined as those having an organic-matter content of 2 percent or more by volume. Contour interval = 100 ft. 1 ft = 0.3048 m.

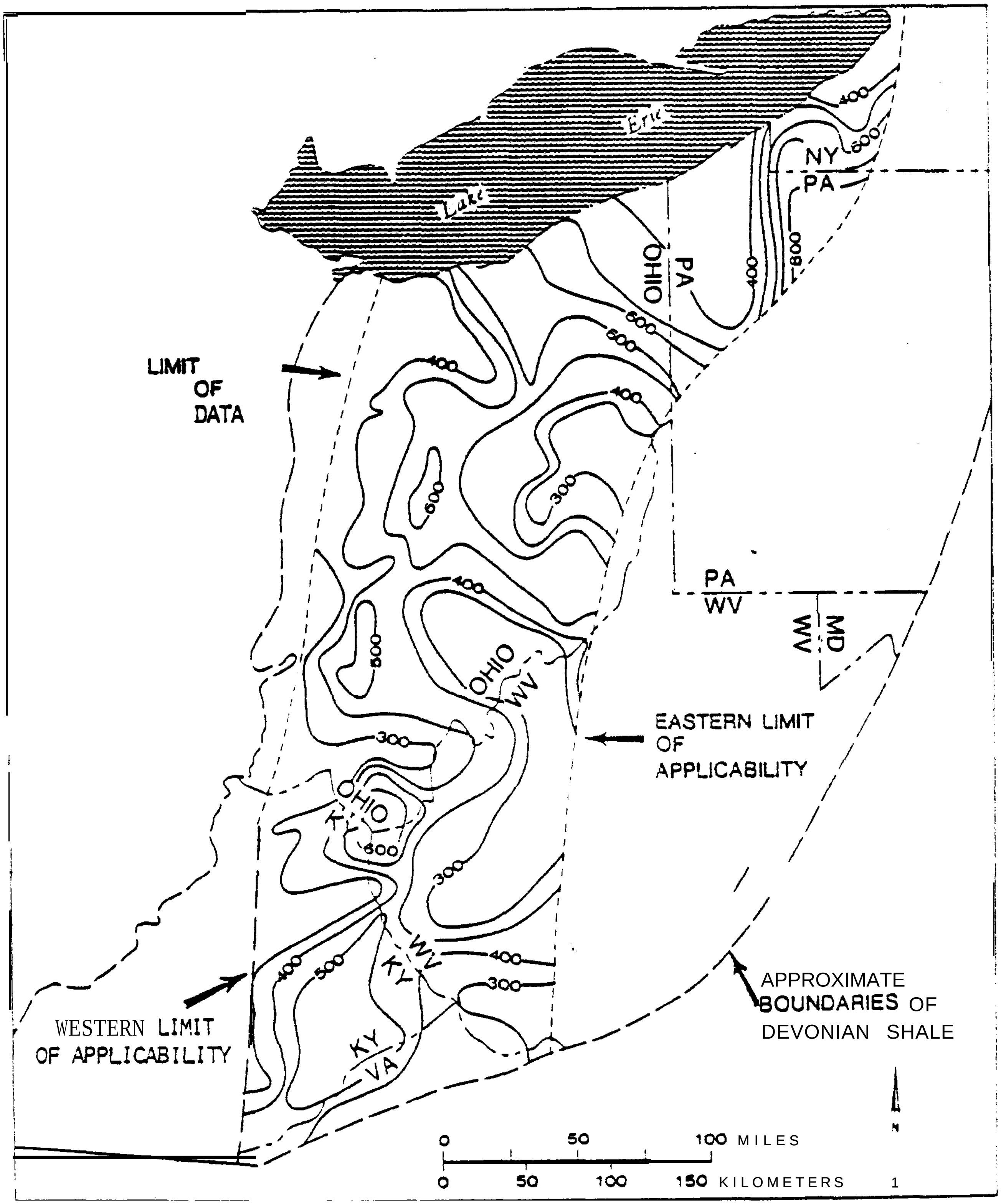

Figure 21.--Thickness (ft) of organic-matter-rich Devonian shale facies (de Witt and others, 1975); organic-matter-rich facies are defined on the basis of the color of well cuttings. Contour interval = 100 ft. 1 ft = 0.3048 m.

Some Devonian shale resource-appraisal methods use as an input the volume of organic-matter-rich ("black") rocks. Comparison of figures 20 and 21 indicates that differences in the definition of organic-matter-rich rocks could lead to differences in the appraisal of the natural-gas resource. The volume of the organic-matter-rich facies contoured in figure 20 is approximately 720 x 10^{12} ft^3 (20.4 x 10^{12} m^3).

Distribution of Organic Matter Within the Organic-Matter-Rich Facies

The average organic-matter content of the organic-matter-rich Devonian shale facies determined from formation-density logs, is shown in figure 22. An increase in average organic-matter content from 5 percent by volume in the eastern part of the mapped area to 16 percent in east-central Kentucky is the dominant regional feature of the map. The organic-matter-rich facies become "blacker" to the west, and facies thickness alone does not characterize the distribution of organic matter.

Figure 23 shows distributions of the average organic-matter content of 40-ft (12.2-m) intervals within the organic-matter-rich facies. The study area is divided into four regions on the basis of political boundaries, and all data in a given region are combined to form a single histogram. Each histogram is a composite that averages intra-regional trends and should not be used to predict quantitatively the organic-matter-content distribution at a given location.

The New York-Pennsylvania and West Virginia histograms are very similar. The most common organic-matter content in these areas is 2 to 4 percent, the maximum organic-matter content is 16 to 18 percent, and the histograms of organic-content values are closely approximated by nearly identical exponential functions. The Ohio histogram shows a relative shift towards higher values of organic-matter content. The best-fit exponential

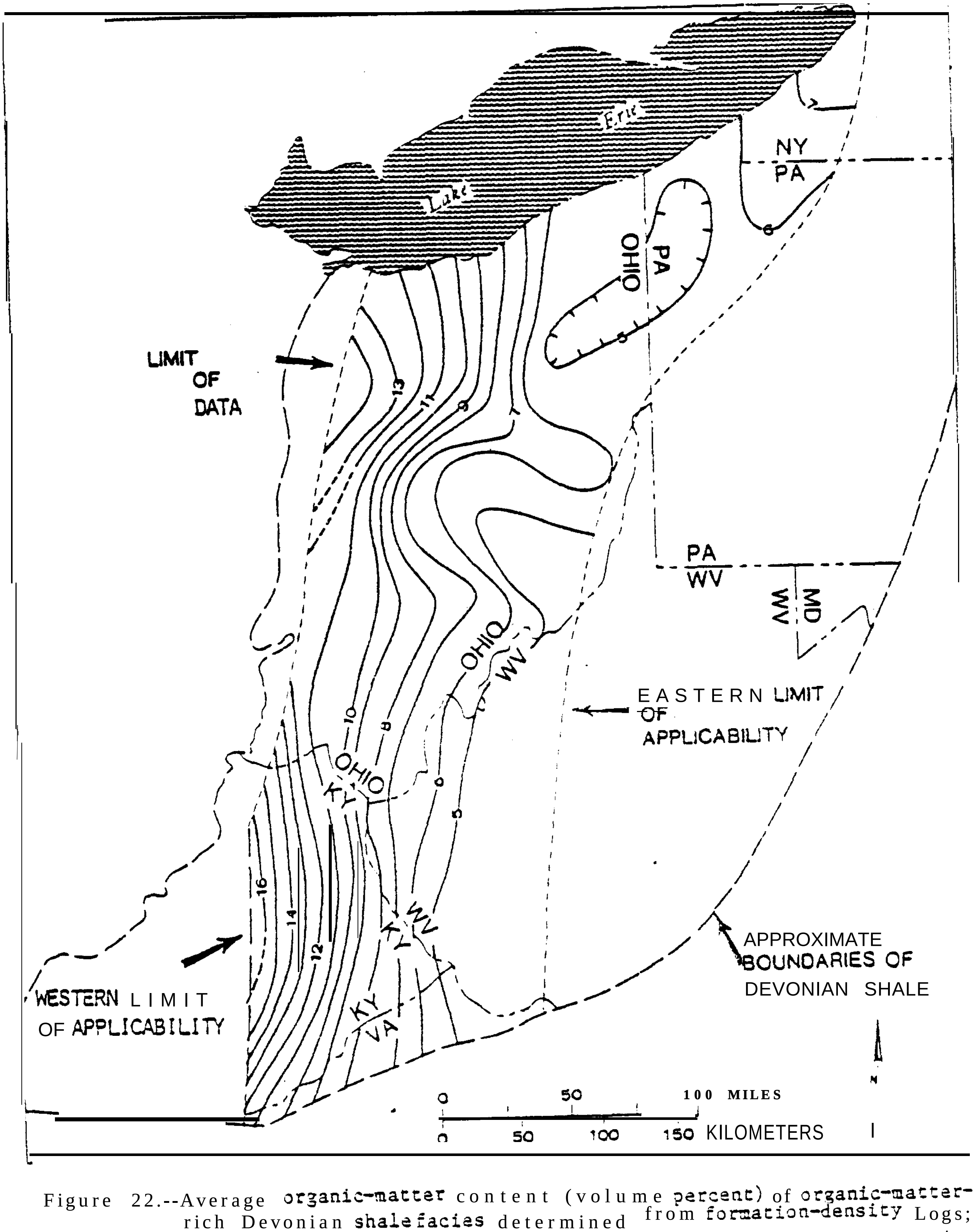

Figure 22.--Average organic-matter content (volume percent) of organic-matter-rich Devonian shale facies determined from formation-density Logs; organicmatter-rich facies are defined as those having an organic-matter content of 2 percent or more by volume. Contour interval = 1 .O percent.

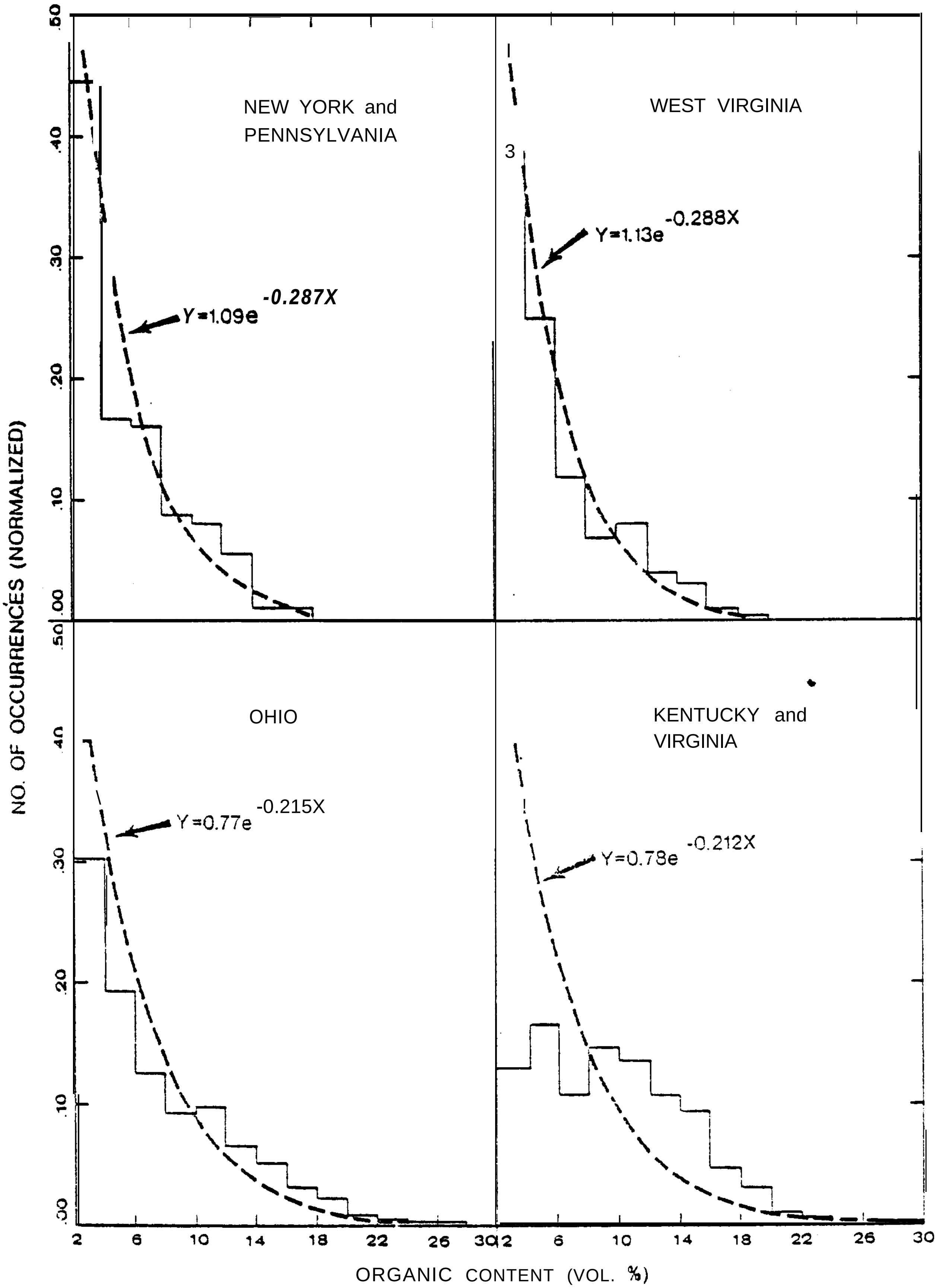

Figure 23.--Histograms of the average organic-matter content determined from formation-density logs of 40-ft (12.2-m) intervals in the organic-matter-rich Devonian shale facies.

curve overestimates the number of occurrences in the 2-10 percent range, and underestimates them for higher percentages of organic matter. In Kentucky and Virginia, organic-matter contents between 2 and 12 percent have approximately equal probabilities of occurrence. For organic-matter contents greater than 12 percent, the likelihood of occurrence decreases linearly to near zero at 24 percent.

Net Thickness of Organic Matter in the Organic-Matter-Rich Facies

The net thickness of organic matter in the organic-matter-rich Devonian shale facies, i.e., the thickness of the blanket of organic matter if all inorganic minerals were removed, is shown in figure 24. Net thickness of organic matter is the product of average organic-matter content (fig. 22) and facies thickness (fig. 20), and defines the amount of organic material incorporated into the organic-matter-rich facies.

Net thickness of organic matter ranges from about 20 to 80 ft (6.1 to 24.4 m) in the study area. A north-trending maximum, along which net thickness of organic matter is greater than 50 ft (15.2 m), extends from eastern Kentucky to Lake Erie. Three areas of local thickening are centered in Martin County, Kentucky, eastern Pike County, Ohio, and northern Ashland County, Ohio.

Figure 24 can be regarded as showing cubic feet of organic material per square foot of surface area. The volume of organic matter can thus be estimated by integrating across the isopleths of figure 24 and is about 50 x 10^{12} ft3 (1.4 x 10^{12} m^3). If the average density of the organic matter is 1.0 g/cm^3 (Smith and Young, 1964), the total mass of organic matter in the organic-matter-rich facies of the Devonian shale in the mapped area is about 3.1 x 10^{15} lb (1.4 x 10^{15} kg).

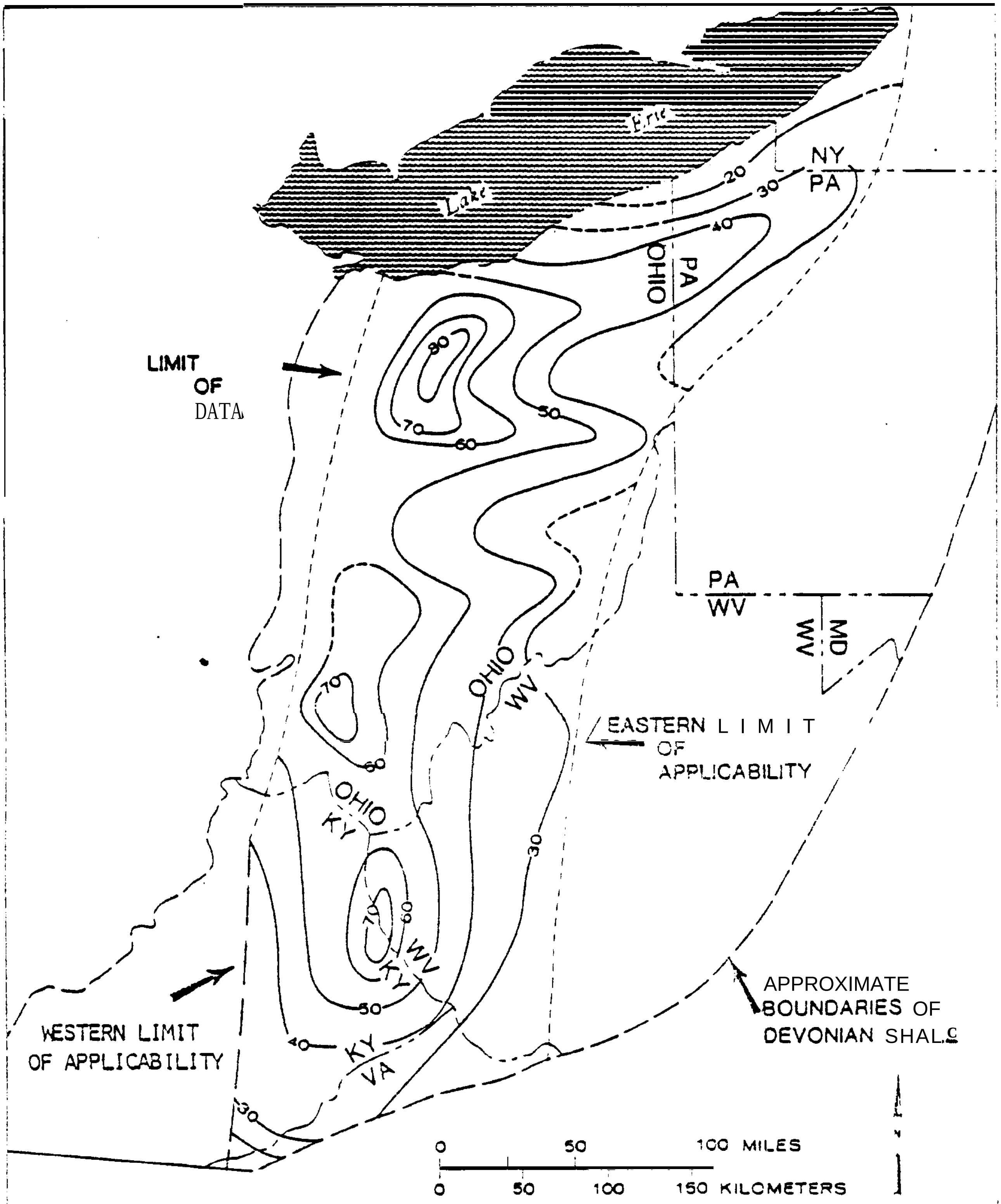

Figure 24.--Wet thickness (Et) of organic matter in the organic-matter-rich Devonian shale facies calculated by multiplying avarage 0 rganic-satter content (fig. 2 2) and facies thickness (f i g . 20). Contour interval = 10 ft. 1 ft = 0.3048 m.

The present distribution of organic matter (fig. 24) probably reflects original depositional characteristics, and trends and proportions probably have been modified only slightly by post-depositional processes. If post-depositional changes have not been significant, figure 24 is an indicator of the organic matter originally available for the generation of hydrocarbons.

SUMMARY

The organic-matter content of the Devonian shale sequence of the Appalachian basin is an important characteristic for assessing the natural-gas resources of these rocks, and patterns of organic-matter distribution convey information on sedimentary processes and depositional environments. Wire-line methods for estimating organic-matter content offer the advantages of economy and continuous sampling of the vertically heterogeneous shale section. They are based on. wire-line logs, which are common and readily available sources of data.

Methods for quantitatively calculating organic-matter content from formation-density and gamma-ray logs are presented in this report. Both approaches are straightforward and require the evaluation of a single equation.

In 12 widely separated test wells, organic-matter content computed from formation-density logs is about as reliable and as accurate as organic-matter content determined by laboratory analyses of core samples. Organic-matter content computed from gamma-ray logs is slightly less accurate than that computed from density logs. Because the Cleveland Member of the Ohio Shale and the lower part of the Olentangy Shale have gamma-ray intensities anomalously lower than gamma-ray intensities of other Devonian shales of similar organic-matter richness, the gamma-ray method for determining organic-matter content is not reliable when applied to these stratigraphic units.

Both methods can be used with confidence in the western part of the Appalachian basin within the region of applicability shown in figure 16. Outside this region, gamma-ray intensity is not a reliable indicator of organic-matter content, and doubt is also cast on the applicability of the density-log method because the gamma-ray intensity does not provide independent confirmation of the fundamental assumptions of the method.

The regional distribution of organic matter in the Devonian shale in the western part of the Appalachian basin is characterized here by showing the thickness of organic-matter-rich facies, the average organic-matter content of the organic-matter-rich facies, the frequency of occurrence of organic-matter-content values, and the thickness of the blanket of organic matter contained in the organic-matter-rich facies. These data are derived from formation-density logs, with organic-matter-rich shale defined as shale' containing 2 percent or more organic matter by voiume.

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